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# THESIS

A COST MODEL FOR ESTIMATING OPERATING AND SUPPORT  
COSTS FOR U.S. NAVY (NUCLEAR) SUBMARINES

by

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June 2000

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**A COST MODEL FOR ESTIMATING OPERATING AND SUPPORT COSTS FOR U.S. NAVY  
(NUCLEAR) SUBMARINES**

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Lieutenant Commander, Supply Corp, United States Navy  
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Submitted in partial fulfillment of the  
requirements for the degree of

**MASTER OF SCIENCE IN OPERATIONS RESEARCH**

from the

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## ABSTRACT

This thesis attempts to formulate a parametric cost model to estimate the annual operating and support (O&S) cost of future U.S. Navy (nuclear) submarines, based on presumed physical characteristics and manpower expectations. Source data for the analysis is obtained from the Navy's VAMOSC database. Using regression analysis techniques, cost estimating relationships are developed for three assumed cost drivers – manpower, length, and submerged displacement. However, the analysis reveals that there is no significant relationship between annual O&S cost and the three assumed cost drivers. Therefore, an alternative method of estimating annual O&S cost is presented using probabilistic assessment of cost based on the empirical annual O&S cost distribution. The probabilistic assessment method allows decision-makers and cost analysts to estimate the annual O&S cost for which there is a desired probability that the true annual O&S cost of a new submarine will not be exceeded. For example, historically, 80 percent of all SSNs have experienced annual O&S costs of less than \$27 M (CY99\$), while the remaining 20 percent have experienced annual O&S costs greater than \$27 M (CY99\$). So, loosely speaking, one can be approximately 80 percent confident that the annual O&S cost of a newly acquired SSN will be no more than \$27 M (CY99\$). Similar results can be obtained for any SSN or SSBN, and for any desired probability.



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## LIST OF ACRONYMS AND ABBREVIATIONS

CCA	Component Cost Analysis
CERs	Cost Estimating Relationships
CES	Cost Element Structure
CY	Calendar Year
DAB	Defense Acquisition Board
DDC	Direct Depot Maintenance Cost
DIC	Direct Intermediate Maintenance Cost
DOD	Department of Defense
DUC	Direct Unit Cost
IC	Indirect Cost
ICE	Independent Cost Estimate
IMA	Intermediate Maintenance Activity
ISR	Individual Ship Report
LOA	Length Overall
LCC	Life-Cycle cost
MDAPs	Major Defense Acquisition Programs
NCCA	Naval Center for Cost Analysis
O&MN	Operations and Maintenance Navy
O&S	Operating and Support
OSD CAIG	Office of the Secretary of Defense Cost Analysis Improvement Group
PPBS	Planning, Programming and Budgeting System
R&D	Research and Development
ROH	Regular Overhaul
SIMA	Shore Intermediate Maintenance Activity
SRA	Selected Restricted Availability
SSBN	Fleet Ballistic Missile Submarine
SSN	Fast Attack Submarine
VAMOSC	Visibility and Management of O&S Costs



## EXECUTIVE SUMMARY

It is currently estimated that over 60 percent of the life-cycle cost of a U.S. Navy submarine is attributable to operating and support (O&S) costs. This thesis attempts to develop a systematic method enabling decision makers and cost analysts to estimate the future annual O&S cost of a newly acquired U.S. Navy submarine.

O&S cost estimates focus on the cost expected to be incurred by a major weapon system (such as a submarine) after it is acquired and deployed. Since there is currently no standardized method for producing reliable estimates of submarine O&S costs, this thesis sets out to formulate parametric cost models that can be used to determine the future annual O&S cost of newly acquired submarines based on assumed physical characteristics and manpower expectations. Similar methods were successfully developed for non-nuclear surface ships (Brandt, 1999).

Source data for this cost analysis was obtained from the Naval Center for Cost Analysis's VAMOSC (Visibility and Management of O&S Cost) database. The VAMOSC database contains historical O&S cost data spanning a period of 14 years for 173 U.S. Navy submarines (as well as data on other types of Navy weapon systems). The data was normalized to constant 1999 dollars (CY99\$), and was partitioned into two sets: fast attack submarines (SSNs) and ballistic missile submarines (SSBNs). SSNs and SSBNs were analyzed separately because of the differences in their missions and overall support structures.

Graphical analysis and robust regression techniques were used to verify the assumption that the source data was free of temporal influences. After the data was validated, cost estimating relationships (CERs) were assumed to exist and were developed using standard regression and data analysis techniques for three presumed cost drivers – manpower, length and submerged displacement. However, the analysis revealed that there was no significant relationship between annual O&S cost and the three presumed cost drivers. More importantly, the analysis revealed that annual O&S costs are roughly the same across all classes within their respective category (SSN and SSBN).

Therefore, an alternative method of estimating annual O&S cost was presented using probabilistic assessment of cost based on the empirical annual O&S cost distribution. The probabilistic assessment method allows decision-makers and cost analyst to estimate

the annual O&S cost for which there is a desired probability that the true annual O&S cost of a new submarine will not be exceeded. For example, analysts can determine that, historically, 80 percent of all SSNs have experienced annual O&S costs of less than \$27 M (CY99\$), while the remaining 20 percent have experienced annual O&S costs greater than \$27 M (CY99\$). So, loosely speaking, one can be approximately 80 percent confident that the annual O&S cost of a newly acquired SSN will be no more than \$27 M (CY99\$). Similar results can be obtained for any SSN or SSBN, and for any desired probability.

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## I. INTRODUCTION

The decision to field a new weapon system, such as a nuclear submarine, requires a commitment to support that system for many years into the future. Decisions to develop, procure, and support new systems are based on many factors, one of which is the projected cost of the systems over their operational lifetime. Operating and Support (O&S) costs normally constitute a major portion of the system life-cycle cost and are critical to the evaluation of acquisition alternatives.

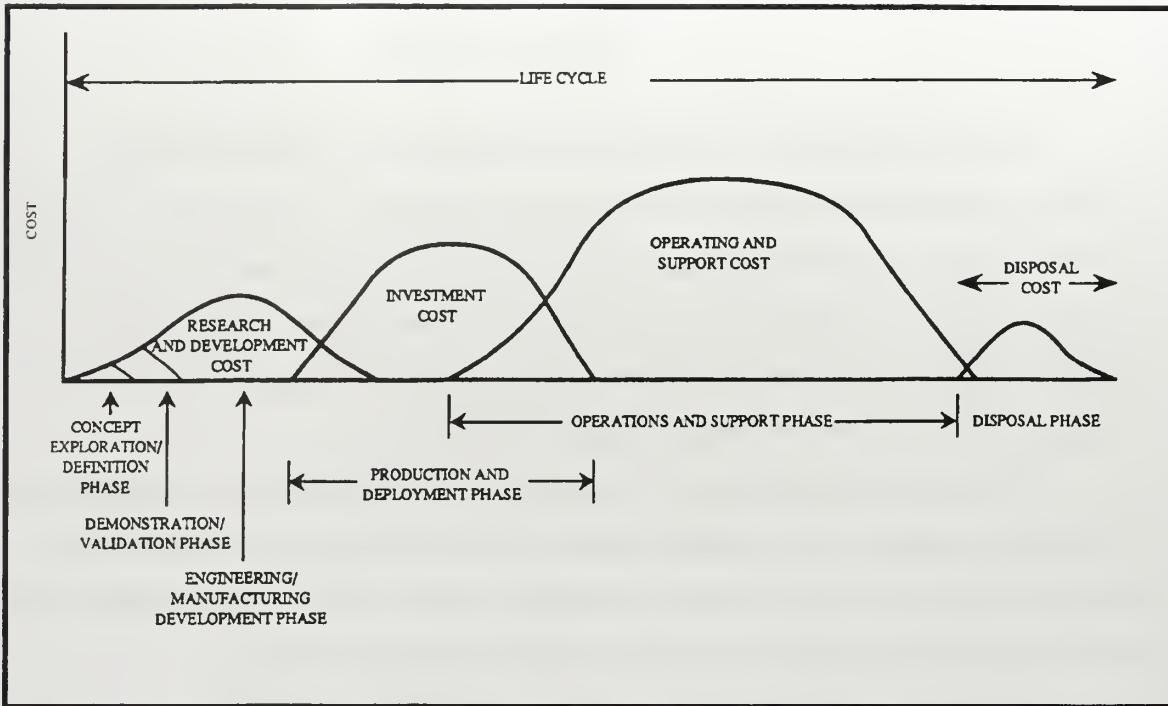
The Department of Defense (DOD) will soon be spending billions of dollars on several new weapons systems, which include three new fighter aircraft, a new attack submarine, and a new fleet of surface combatants. Many of these weapon systems will cost at least twice as much as the systems they are designed to replace.

To better manage cost, the decision-maker must focus on expenses associated with owning the weapon system, not just initial purchase price. For the Navy alone, estimates show that about 64 percent (OSD CAIG, 1992) of the life-cycle<sup>1</sup> cost of major weapon systems can be attributed to O&S costs. In order to execute future modernization and acquisition plans affordably, the Navy (and DOD) must understand and manage the total ownership cost of weapon systems. For purposes of cost estimating, life-cycle costs are typically divided into four components: research and development, investment, operating and support, and disposal.

Figure 1 illustrates the program life cycle and shows the various levels of a system's life cycle cost. The Figure is intended for illustrative purposes and may not depict actual program patterns. To show how the cost distribution can vary from one program to the next, Figure 2 provides a percentage breakout of the costs incurred during the key acquisition phases for two different weapon systems.

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<sup>1</sup> The life-cycle of a weapon system begins with the determination of a mission need and continues through the engineering and manufacturing development, production and deployment, and operations and support phases to the eventual disposal of the system by the government.



**Figure 1. Illustration of Program Life Cycle Cost by Acquisition Phase (OSD CAIG).**

For purposes of cost estimating, life-cycle costs are typically divided into four components: research and development, investment, operating and support, and disposal. This Figure illustrates the program life cycle and shows the various phases of a system's life cycle cost. The Figure is intended for illustrative purposes and may not depict actual program patterns. For the Navy alone, estimates show that about 64 percent of the life-cycle cost of major weapon systems can be attributed to O&S costs.

The following paragraphs summarize the primary cost categories associated with each life-cycle phase.

- **Research and Development.** Consists of costs incurred from program initiation at Concept Demonstration and Approval (Milestone I) through the Engineering and Manufacturing Development phase. Includes costs of feasibility studies; modeling; trade-off analyses; engineering design; development, fabrication, assembly, and test of prototype hardware and software; system tests and evaluation; system- specific support equipment; and documentation.
- **Investment.** Consists of costs incurred during the Production and Deployment phase (from Milestone III though completion of deployment). Encompasses costs associated with producing, procuring, and deploying the primary hardware and directly associated hardware and activities, such as system-specific support equipment, training, data, initial spares, and military construction.
- **Operations and Support.** Includes all costs of operating, maintaining, and supporting a fielded system. Encompasses costs for personnel;

consumable and repairable materials; organizational, intermediate and depot maintenance; facilities; and sustaining investment. The O&S phase overlaps with the Production and Deployment phase. O&S costs are incurred in preparation for and after a system's fielding and continue through the end of the system's useful life.

- **Disposal.** Captures costs associated with deactivating or disposing of a military system at the end of its useful life. These costs typically represent only a small fraction of a system's life-cycle cost and are excluded from most analyses. The main exceptions (for which estimates must be provided) are disposal of nuclear waste, missile propellants, and other materials requiring detoxification or special handling. Note: this study does not attempt to quantify disposal costs of nuclear submarines.

	<u>R&amp;D</u>	<u>Investment</u>	<u>O&amp;S</u>
<b>F-16 Fighter</b>	2%	20%	78%
<b>M-2 Bradley Fighting Vehicle</b>	2%	14%	84%

**Figure 2. Percentage of Life-Cycle Costs Incurred in Various Program Phases (OSD CAIG).** To show how the cost distribution can vary from one program to the next, this Figure provides a breakout of the costs incurred during the key acquisition phases for two different weapon systems. Disposal Costs were not available for this example.

An appropriate O&S cost model should be able to estimate O&S cost early on in the Research and Development phase of the weapon system acquisition process. The proposed O&S cost model is parametric in that a statistical approach is used to estimate the functional relationship between cost and assumed major cost drivers<sup>2</sup>.

<sup>2</sup> Cost drivers are characteristics of a system or subsystem that have a large or major effect on the system's cost.

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## II. BACKGROUND

### A. OPERATING AND SUPPORT COST ESTIMATING

Discussion on operating and support (O&S) cost estimating is obtained from the Operating and Support Cost Estimating Guide prepared by the Office of the Secretary of Defense (OSD) Cost Analysis Improvement Group (CAIG). As delineated in DOD instruction 5000.2M<sup>3</sup> and DOD directive 5000.4<sup>4</sup>, the OSD CAIG acts as the principal advisory body to acquisition milestone decision authorities on cost-related issues. The guide, prepared by OSD CAIG, is for use by all DOD components, and, as stated explicitly in the manual itself, “should be considered the authoritative source document for preparing O&S cost estimates.”

The life-cycle cost (LCC) estimate is an important tool for measuring affordability. For Major Defense Acquisition Programs (MDAPs), the LCC is composed of all costs related to a major weapon system during its life span; these include research and development (R&D), production, O&S, and disposal costs. As seen previously in Figure 1, O&S costs typically exceed both R&D and production costs over a system’s useful life.

Therefore, in assessing the total cost associated with acquisition alternatives and affordability, the O&S cost for each system must be a primary consideration. Moreover, independent review and validation of O&S cost estimates is critical for informed decision-making about the procurement of major weapon systems that will require a financial commitment to O&S cost demands for many years into the future. The LCC estimate, which is required to support the planning, programming, and budgeting system (PPBS) among other things, serves as the basis for a program office’s budget submittal in support of specific milestone requirements for MDAPs.

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<sup>3</sup> "Defense Acquisition Management Documentation and Reports," dated February 23, 1991. DoDD 5000.2-M establishes procedures and formats for various acquisition-related reports, such as milestone documentation, periodic in-phase status reports, and statutory certifications. The manual is intended for direct implementation by the DoD components without supplementation.

<sup>4</sup> "OSD Cost Analysis Improvement Group" (revised edition forthcoming). DoDD 5000.4 establishes the CAIG and describes its responsibilities as the cost-estimating advisor to the DAB. It also establishes requirements for preparing and presenting estimates to the CAIG.

In order to test the reasonableness of the program office's estimate (POE) for LCC, an independent agency within the DOD cost community prepares a component cost analysis (CCA) or independent cost estimate (ICE). The CCA or ICE functions as a crosscheck for the POE at each acquisition milestone decision.

In some circumstances, the OSD CAIG evaluates the CCA against its own ICE for the MDAP. Following its review, the CAIG submits its cost position to the Defense Acquisition Board (DAB), a senior DOD corporate body for major weapon systems acquisition that provides advice and assistance to the defense acquisition executive (the Undersecretary of Defense for Acquisition, Technology and Logistics) and the Secretary of Defense. The DAB makes the decision for each program milestone based on the cost position and other factors.

The objective of this study is to develop a rough order-of-magnitude and robust O&S cost estimating methodology for U.S. Navy submarines that will generate reliable O&S cost estimates for new submarine acquisition programs.

## **B. THE NAVAL CENTER FOR COST ANALYSIS**

By direction of the Secretary of the Navy, the Naval Center for Cost Analysis (NCCA) was established on October 1, 1985. Its mission is to "to guide, direct and strengthen cost analysis within the department of the Navy; to ensure the preparation of credible cost estimates of the resources required to develop, procure and operate military systems and forces and support of planning, programming, budgeting and acquisition management; and to perform such other functions and tasks as may be directed by higher authority." NCCA is one of the four DOD cost centers that develop CCA's and ICE's for MDAPs<sup>5</sup>.

One of NCCA's vital functions is to manage the Department of the Navy's portion of the congressionally mandated Visibility and Management of Operating and Support Costs (VAMOSC) program.

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<sup>5</sup> The other three are the Army's Cost and Economic Analysis Center (CEAC), The Air Force Cost Analysis Agency (AFCAA) and the DOD CAIG.

## C. VISIBILITY AND MANAGEMENT OF OPERATING AND SUPPORT COSTS (VAMOSC)

The Visibility and Management of Operating and Support Costs (VAMOSC) database is one source of historical cost data specifically directed by DoDD 5000.4<sup>6</sup>. An historical data collection system, VAMOSC records O&S costs in a well-defined, structured approach for most Navy major weapon systems (a U.S. Navy submarine is considered a major weapon system).

One of the objectives of VAMOSC is to enhance the visibility of O&S costs for these systems for use in DOD cost analyses. Validated VAMOSC data should be used to calculate the O&S cost of MDAPs unless some other source of data is clearly more appropriate (OSD CAIG, 1992). The data is intended to be used as a basis for decisions concerning affordability, budget development, support concepts, cost trade-offs, modifications, and retention of current systems. The OSD CAIG, responsible for VAMOSC implementation and guidance, also encourages use of the data to develop cost estimates for future systems.

The individual ship report (ISR) of the Navy VAMOSC database which was provided for this study forms the basis for the data analysis and cost model formulation. The estimated total annual O&S cost for each submarine is broken down into four primary component cost elements:

- direct unit cost (DUC)
- direct intermediate maintenance costs (DIC)
- direct depot maintenance costs (DDC)
- indirect cost (IC)

Appendix A illustrates the complete cost element structure (CES) defined by VAMOSC. A summary description of the four primary submarine O&S cost components and their associated sub-elements follows from detailed discussion in the Navy VAMOSC Individual Ship Report (ISR).

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<sup>6</sup> DoDD 5000.4 requires that historical data be used to identify and allocate functional costs among major defense systems and subsystems.

## 1. Direct Unit Cost (DUC)

Direct unit cost captures the direct costs associated with the operation and support of an individual submarine as identified by its unit identification code. It is computed within the Navy VAMOSC Management Information System. The major sub-elements of direct unit cost are;

- personnel
- material
- purchased services

A key sub-element in this aggregation is manpower cost. This cost includes base pay, allowances, other entitlements and government contributions to FICA and SGLI, but does not include the indirect cost of trainees, unassigned personnel, permanent change of station personnel, patients, etc.

Material cost sums the cost of all materials utilized or consumed by the ship with the exception of materials utilized in the intermediate and depot level maintenance effort. The materials accounted for herein include ship petroleum, oil and lubricants (POL), repair parts (non-aviation depot level repairables), supplies, and training expendable stores <sup>7</sup> (purchased from procurement appropriations).

Purchased services cost covers the cost of services other than maintenance. These include printing and reproduction, ADP rental, contract services, rent, utilities, and communications.

## 2. Direct Intermediate Maintenance Cost (DIC)

Direct intermediate maintenance costs include the cost of material and labor expended by a tender, repair ship or equivalent ashore or afloat intermediate maintenance activity (IMA) in the repair and alteration of the submarine. The major sub-elements of direct intermediate maintenance costs are;

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<sup>7</sup> Includes the cost of ammunition, training missiles, and pyrotechnics expended by the ship in non-tactical operations and training exercises.

- afloat maintenance labor
- ashore maintenance labor
- material
- commercial industrial services

Computed within the Navy VAMOSC database, afloat maintenance labor cost includes the cost of labor expended by a tender, repair ship or equivalent afloat IMA for the repair and alteration of the ship being tended. Similarly, ashore maintenance labor cost covers the cost of labor extended by a shore IMA (SIMA). The cost of repair parts and consumables used by the IMAs are included within the material cost sub-element. Finally, commercial industrial services cost captures the cost of accomplishing afloat and ashore intermediate maintenance actions by private contractors due to workload limitations at the IMAs.

### **3. Direct Depot Maintenance Cost (DDC)**

Costs associated with depot-level maintenance performed for the ship by public or private facilities are classified as direct depot maintenance cost. The major sub-elements of direct depot maintenance costs are;

- scheduled ship overhaul
- nonscheduled ship repair
- fleet modernization
- other depot

These costs are computed within the Navy VAMOSC database, using data provided by various sources. The expenditures of scheduled depot maintenance support, for Regular Overhaul (ROH) and Selected Restricted Availability (SRA), of ships in the operating forces incurred at both public and private facilities constitute scheduled ship overhaul cost. Nonscheduled ship repairs cost, in contrast, records the cost of depot-level maintenance expended as the result of casualty, voyage damage, and other unforeseeable occurrences which remain beyond the repair capability of the ships force.

Fleet modernization cost sums the costs of installing ship alterations and improvements (including military and technical), other support provided at ship depot

facilities, and costs for centrally provided material used at public and private facilities. Costs expended for the purchase of spare parts and other material required due to changes in the ships Consolidated Shipboard Allowance List are also included.

#### **4. Indirect Costs (IC)**

Indirect O&S cost captures the cost of those non-investment services and items that are required by the ship after commissioning and launching to continue operations but which do not result in an expense against Fleet Operations and Maintenance, Navy (O&MN) appropriations. The major sub-elements of indirect operating and support costs are:

- training
- publications
- engineering and technical services
- ammunition handling

These costs are computed within the Navy VAMOSC database, and are calculated by the summation of cost sub-elements of training (professional skill classroom instruction for officers and enlisted), publications, engineering and technical services (services provided to the submarine other than during IMA or depot availability), and ammunition handling.

### III. DEVELOPING A PARAMETRIC COST MODEL

#### A. THE PARAMETRIC COST ESTIMATING PROCESS

##### 1. Collection, Normalization, and Evaluation of Historical Cost and Parametric Data

Parametric cost estimation requires an extensive database of historical cost. The VAMOSC database offers the advantage of actual observations which show both expected and unusual cost expenditures of fielded systems

The cost data must be normalized to account for environmental impacts such as inflation. Additionally, the data must be transformed into a format suitable for analysis and a partitioning of the data into two types, SSN and SSBN type submarines for consistency of scope (sample homogeneity). After the historical data is normalized (ex. inflation), data analysis and regression will be used to evaluate the assumption that O&S costs are constant from year to year within any class so that the class average and its associated variance can be used in formulating a CER. It is assumed that there exists a functional relationship between cost drivers and O&S cost. A cost driver or parameter is simply a physical, performance or technological characteristic that is used to predict cost at a high level of aggregation: a "top -- level" cost estimate. The nature of this relationship will be determined through regression analysis.

##### 2. Cost Estimating Relationships

Cost estimating relationships (CERs) are "... mathematical expressions relating cost of a dependent variable to one or more independent cost driven variables." (Parametric Cost Estimating Handbook, 1995) There are four common approaches to developing a CER:

- Analogy
- Industrial Engineering approach
- Expert Opinion
- Statistical/Parametric approach

The statistical or parametric approach is generally the preferred method of cost estimation and is used in this thesis

## **B. THE PROPOSED TOTAL ANNUAL O&S COST MODEL**

A parametric cost model is defined as "... a group of cost estimating relationships (CER's) used together to estimate entire cost proposals or significant portions thereof" (Parametric Cost Estimating Handbook, 1995). Parametric cost models link O&S cost with the major weapon system's physical, performance, and technical parameters. It is assumed that a cost estimating relationship exists between a size parameter and O&S cost. Cost is represented by the expenditure of total annual O&S dollars. Here the major weapon system is a submarine.

### **1. Cost Model Methodology**

This study attempts to construct a parametric cost model for estimating total annual O&S cost for U.S. Navy submarines based on one of the three specific size (physical) parameters: submerged displacement (tons), length overall (LOA) in feet, and manpower (crew size). A historic cost database detailing the total annual O&S cost of 175 submarines is normalized for inflation, purged of submarine classes that are non-nuclear and evaluated for consistent cost trend relationships (using graphical techniques, linear regression and robust linear regression). CERs will be applied to the two submarine categories (SSN and SSBN) to obtain a rough order-of-magnitude O&S cost estimate.

The model will also provide total O&S cost broken down into four primary OSD CAIG O&S cost components for each category.

### **2. Cost Model Documentation and Validation**

The documentation of a parametric model should include the source of data used to derive the parameters, the size and range of the database. Additional information that should be included in the documentation of a parametric model is: how the parameters were derived, the limitations of the model, the time frame of the database, and how well the parametric model estimates its own database.

## IV. DATA ANALYSIS

### A. DATA COLLECTION AND NORMALIZATION

The VAMOSC submarine data was provided by NCCA in a spreadsheet format (see Appendix A for a sample of the raw data). The data reflects annual O&S cost from fiscal year 1984 through 1997. Two classes in the database were non-nuclear powered submarines and were subsequently excluded since the scope of the study extends only to nuclear-powered submarines. SSBN 598 class was removed from the study because it had only one observation point and was missing data. The SSN 640 class, two special operations boats converted from an SSBN 640 class hull, was missing numerous entries and was therefore removed from the study. The purged database contains O&S costs for 175 submarines spanning 13 classes. All cost data received in the database was normalized to constant 1999 dollars (CY99\$) to remove the effects of inflation. Table 1 summarizes the database in terms of submarine class, the number of submarines in the class, years of data and comments.

Submarine Class	# in Class	Years of Data	Comments
SS 576	1	N/A	Removed/Non-Nuke
SS 580	3	N/A	Removed/Non-Nuke
SSN 575	1	3	
SSN 578	3	5	
SSN 585	5	6	
SSN 594	13	12	
SSN 597	1	4	
SSN 608	3	8	
SSN 637	37	14	
SSN 640	2	6	Removed/Data missing
SSN 671	1	14	
SSN 685	1	6	
SSN 688	62	14	
SSBN 598	1	1	Removed/1 year of data
SSBN 616	19	11	
SSBN 640	12	11	
SSBN 726	17	14	

**Table 1. Submarine Database Summary.** The data is summarized by submarine class, the number of submarines in the class, years of O&S cost data and why some classes were removed from the analysis. Although the SSBN 616 and 640 classes have the same physical size parameters they are significantly different internally and are considered separate classes.

Observations in this database consist of the O&S cost associated with a particular submarine in a particular year. In each observation, the total annual O&S cost is broken down into 122 cost elements in accordance with the VAMOSC Defined Cost Elements Structure (CES). For a complete breakdown of this structure see Appendix A. For this study the 122 CES's are aggregated into the four major cost components, as discussed in chapter 2, representing the total annual O&S cost. A detailed review of the database revealed continuity in all CESs across all years with the exceptions noted above.

The scope of the database is further refined into two categories. The 13 classes of submarines can be partitioned into SSNs and SSBNs. This analysis will consider all submarines that are not ballistic missile submarines as fast attack submarines because research and one-of-a-kind classes more closely resemble SSN characterization. This is a natural partitioning of the set of all submarines because of differences in mission, maintenance and crew makeup between the two. The two categories will be analyzed separately to achieve parity of content and consistency of scope. For brevity, the three largest classes within each category, which constitute 93% of all SSN observations and 100% of SSBN observations, are presented for in this chapter. These classes are SSN 594, 637, 688, and SSBN 616, 640 and 726.

## **B. ASSUMPTIONS VALIDATION**

### **1. Assumptions**

Since the development of the predictive cost model is based on all annual O&S cost observations from a class, the first step of the data analysis is to validate two assumptions. Specifically, for a given ship class:

- on average, annual O&S cost for any submarine within a class does not change from year to year; and
- the collected annual O&S cost observations can be viewed as coming from a random sample drawn from a hypothetical population of such submarines.

In consideration of the first assumption, we might logically think that as a submarine grows older, maintenance and upkeep costs should increase, which is one possible indication of time-dependent behavior, however, that was not found to be the

case. For the second assumption, although the VAMOSC submarine database reflects the entire population of Navy submarine classes, the collected database is viewed as a sample of submarines taken from the entire population of possible past, present, and future submarines for purposes of this analysis. This allows us to use the tools of statistical theory to assess the significance of different factors.

Effectively, the objective of the graphical analysis and regression analysis in the initial stage of the cost model development is to validate the assumptions that class O&S costs within each class are approximately constant over time and that the O&S cost for each submarine in a class is indistinguishable, year to year, from others in that class.

## C. GRAPHICAL ANALYSIS

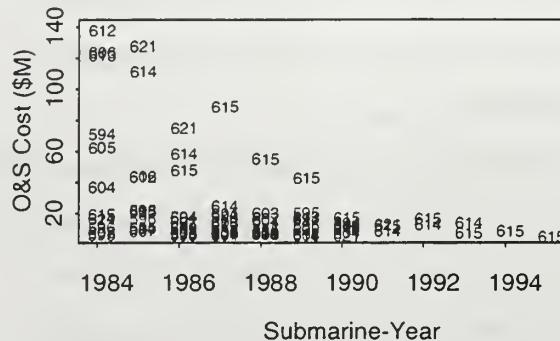
The graphical analysis is an exploration of the database to help understand the character of the data and help clarify and interpret our findings.

### 1. Scatter Plots

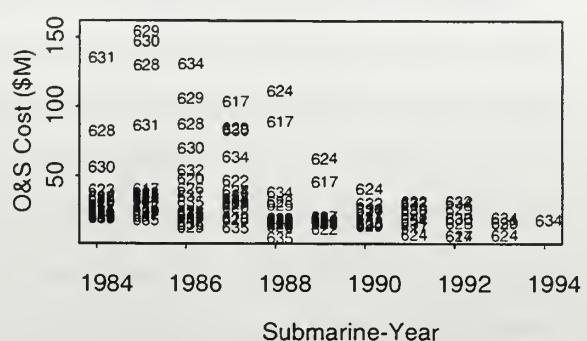
Scatter plot analysis of O&S costs over time will develop a visual feel of how O&S costs vary over time. Figure 3 shows the scatter plots for the six classes of submarines identified earlier. The scatter plot uses the submarine's hull number to denote an observation. This helps to conclude that individual submarine O&S costs are indistinguishable, year to year, from others in their class. All of the classes show a significant amount of scatter predominantly in the higher cost areas.

The SSN 594 and 637 and SSBN 616 and 640 classes show many extreme O&S cost observations. These extreme O&S cost observations are scattered significantly above the bulk of the observations and tend to decrease over time. It appears that as submarines from these classes were decommissioned, the number of extreme observations decreased rapidly and converges to the bulk of O&S cost observations for these classes. This runs counter to the idea that O&S costs would tend to increase over time due to years of service. These classes were being decommissioned during the time frame of the database. The SSN 688 class has extreme observations more uniformly distributed over time. This class of submarine has experienced some decommissioning but not to the extent that others have.

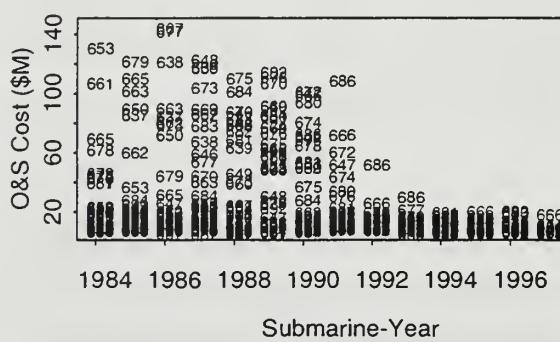
SSN-594 Class



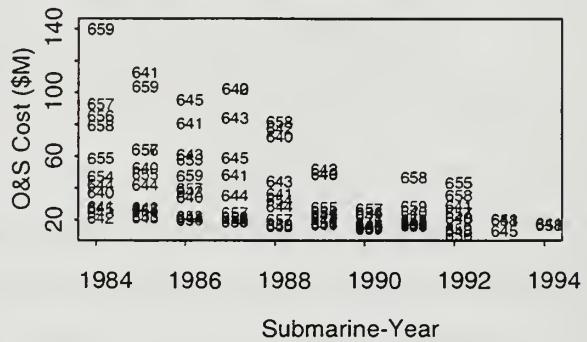
SSBN-616 Class



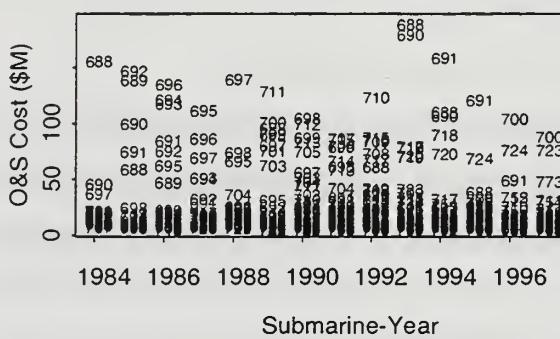
SSN-637 Class



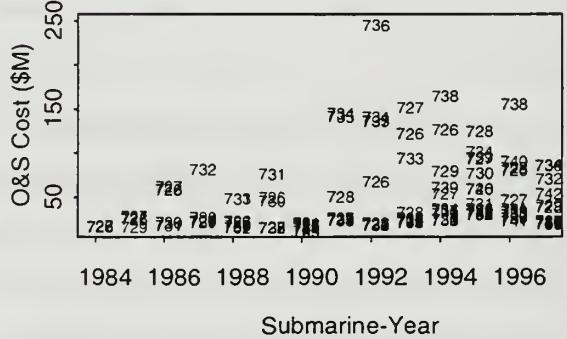
SSBN-640 Class



SSN-688 Class



SSBN-726 Class



**Figure 3. Scatter Plots of O&S Cost and Submarine-Year Depicted by Hull Number.** All six classes show significant amounts of scatter predominantly in the higher cost area. Use of the submarine hull numbers to depict the O&S cost observation for that year helps conclude that individual submarine O&S costs are indistinguishable, year to year, from others in that class. The 594, 637, 616, and 640 classes, now retired, show a decrease in extreme O&S cost observations as the class nears retirement. The 688 class shows a more even distribution of extreme observations and the 726 class shows an increase in extreme observations as the class enters the fleet. Extreme observations appear to be a normal part of submarine O&S costs, and may be due to reactor refueling.

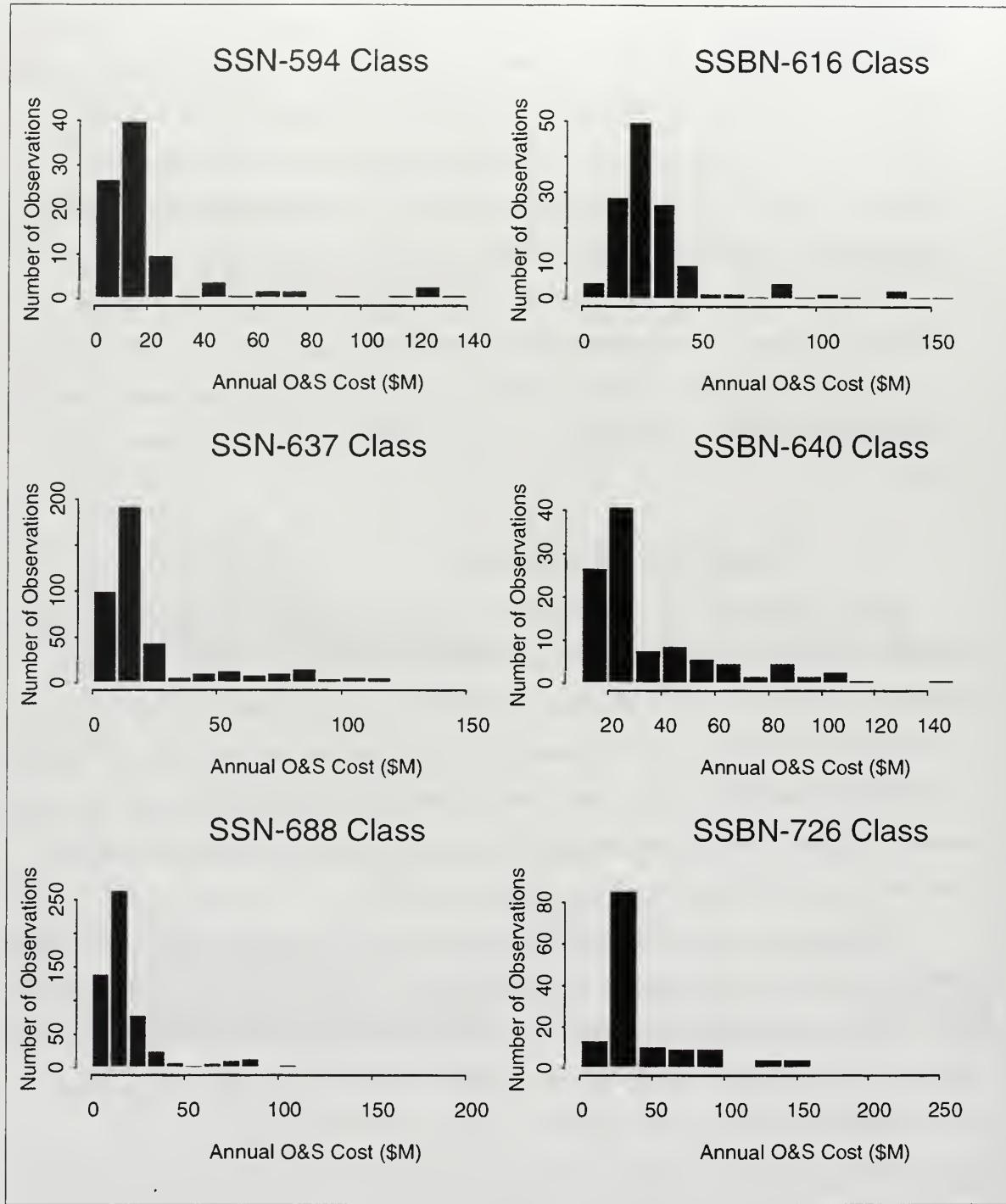
The SSBN 726 class shows the opposite of this effect. As more 726 class submarines come online the number of extreme observations increase. The overall synopsis is that all classes of submarines have extreme observations which appear to be a natural component of their O&S costs but the frequency of these observations decrease significantly when the class approaches retirement. It is suspected that these extreme observations are related to reactor refueling.

However, as a class comes on-line through commissioning these extreme observations increase. These extreme O&S cost observations (outliers), which will be shown later, are primarily a function of direct unit cost and direct depot maintenance cost. The next step will be to use histograms to see how O&S costs are distributed within a class.

## **2. Histograms (Total O&S costs)**

The distribution of cost within a class will give us a better indication of where the average O&S costs lie and see how the extreme observations are distributed. The histograms in Figure 4 shows the number of O&S cost observations that falls within an O&S cost dollar range or bin. For example a submarine that was in operation from 1984 to 1997 will contribute 14 O&S cost observations and each observation based on its cost will be assigned a bin. All the histograms are skewed to the right and show that most submarines have an annual O&S cost well below \$50 M.

Although the bulk of the O&S cost is below \$50 M there are observations that are well above \$50 M, corresponding to the extreme observations identified in the scatter plots earlier. We also notice that there are more extreme high-cost observations than there are low-cost observations relative to the average. This also shows that the extreme observations are not evenly distributed on either side of the average but reside predominantly above the average. The extreme observations are quite far away from the bulk of the data and could have a significant effect on our regression analysis later on.



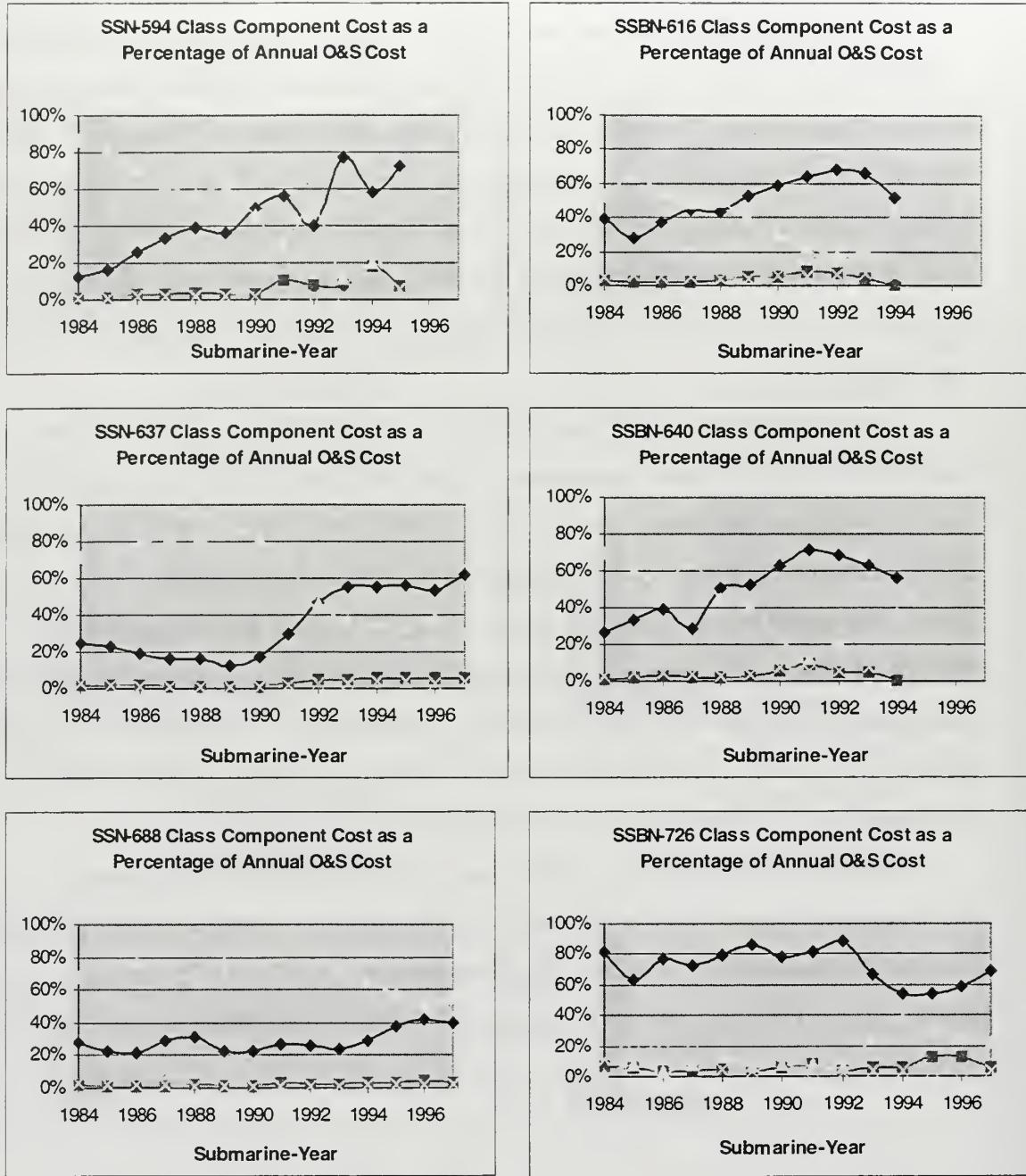
**Figure 4. Histogram Plot of Annual O&S cost and Observation counts.** All the histograms are skewed to the right corresponding to the large number of extreme O&S cost observations shown in the scatter plots. The majority of the O&S cost observations are well below \$50 M. The extreme observations will have a significant effect on the regression analysis later on.

### 3. Component O&S Costs by Percentage

O&S costs will be decomposed into four major components and transformed into a percentage of the total O&S cost to see which component contributes the most to the extreme observations. The graphs in Figure 5 sum each of the four component O&S costs for all submarines in a class and year and then divide each component cost by the total O&S cost for that class and year. This provides a snapshot, by percentage, of how the total O&S cost is distributed among the four component costs. It is interesting to note that direct unit cost and direct depot maintenance cost make up the largest percentage of total O&S costs.

For the SSN 594 and 637 and SSBN 616, and 640 classes the direct depot maintenance cost component commands a higher percentage of the total annual O&S costs early on and then drops off taking a lower percentage of the total O&S costs. Recall that the extreme observations for these classes were also decreasing over time. It will be shown later that direct unit costs are fairly constant over time so that the apparent increase of direct unit cost as a percentage of the total O&S cost is because direct depot maintenance costs decrease sharply overtime. It appears that as a submarine class reaches the end of its useful life and begins retiring, by decommissioning its units, direct depot maintenance cost will command a lesser share of the total O&S costs.

The SSN 688 class shows a fairly steady percentage of the direct depot maintenance cost then shows a decrease in the last few years when a number of its units were decommissioned. The SSBN 726 class shows a completely different picture in that direct unit cost takes the lion's share of the total O&S costs for that class from the onset.



**Figure 5. Four Major Component Costs Broken Out as Percentages of the Total O&S Cost.** The legend is as follows, Diamond for direct unit cost, Square for direct intermediate maintenance cost, Triangle for direct depot maintenance cost and X for indirect cost. The four major component costs (DUC, DIC, DDC and IC) are shown as a percentage of the total O&S cost for a submarine-year. DUC and DDC are the major contributor to the total O&S cost. The 594, 637, 616 and 640 classes show that DDC dominates DUC as the major contributor to annual O&S cost but as the classes are retired it takes on less importance. DUC becomes the major contributor not because it increases in cost in later years but because DDC decreases rapidly, which will be shown later. The 688 class shows DDC dominating DUC but takes a dip when some of the 688s were decommissioned. The 726 class shows the opposite with DUC dominating DDC.

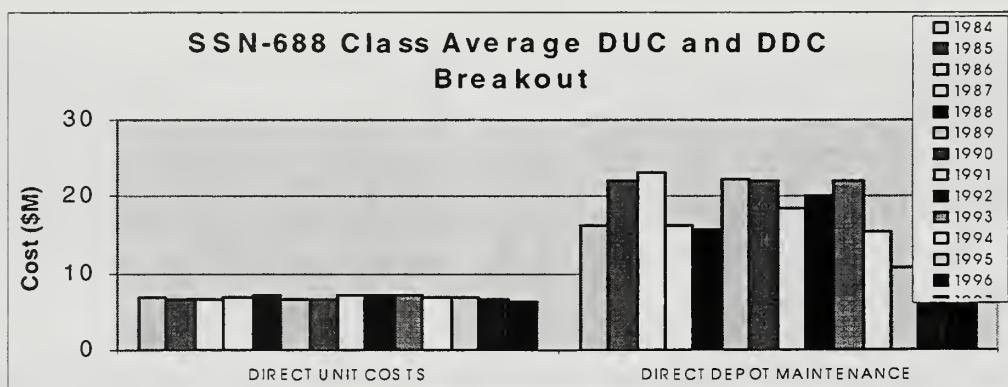
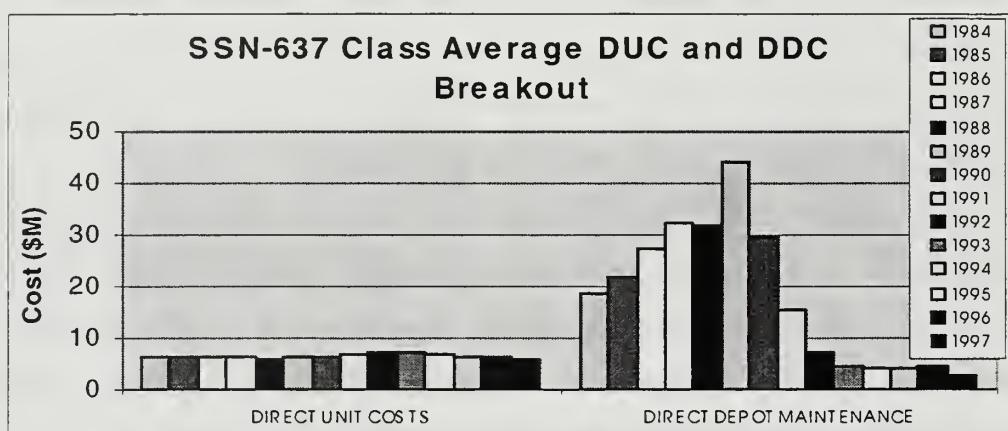
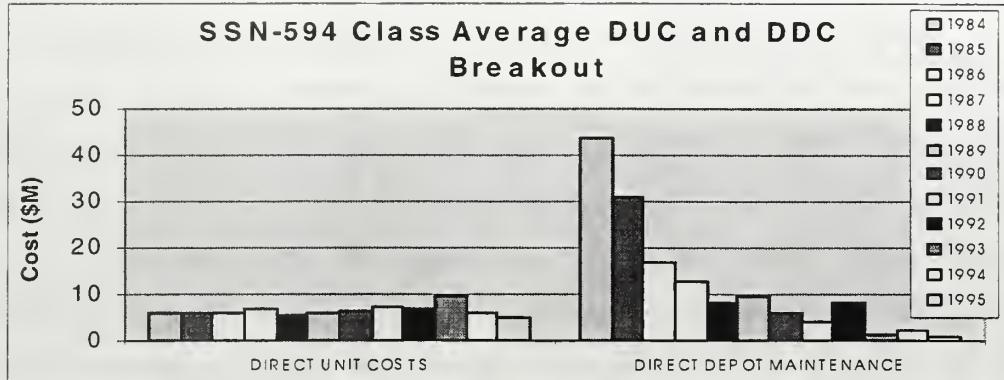
#### **4. Direct Unit and Direct Depot Maintenance Costs by Average**

A further look into the average sub-component costs will be conducted to determine what component and sub-component influences the extreme O&S cost observations. Figures 6 and 7 examine the average direct unit costs and direct depot maintenance costs. Each sub-component is summed for all submarines in a class and year and divided by the total number of submarines in the class that year.

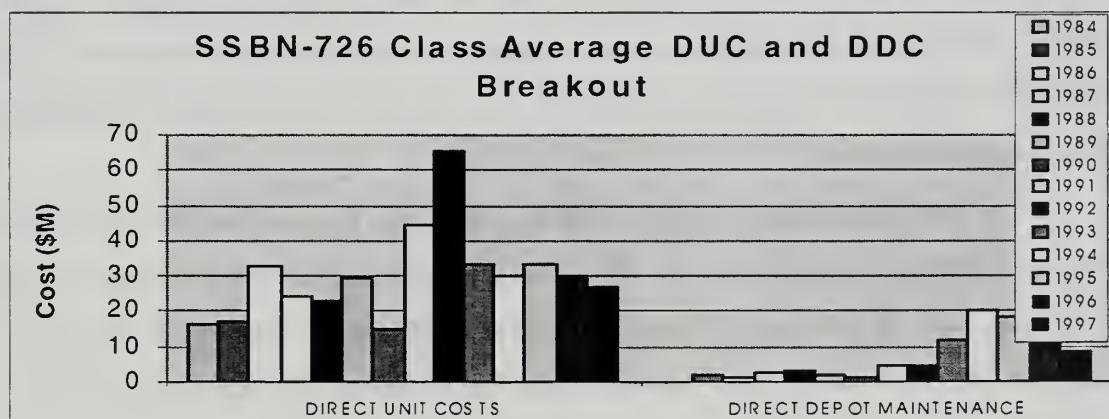
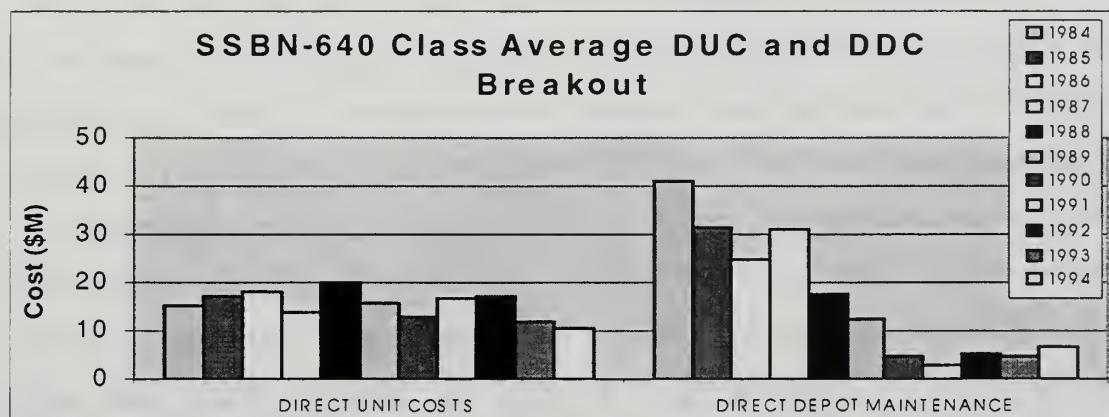
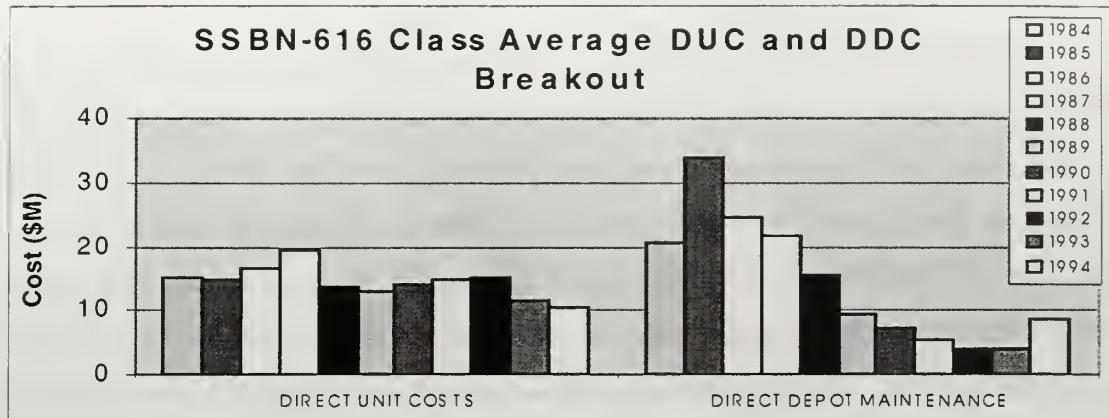
The sub-components of direct unit cost for the SSN 594 and 637 and SSBN 616 and 640 classes tend to be constant from year to year. The explanation for the extreme observations is in the direct depot maintenance cost component, which includes scheduled ship overhaul and fleet modernization sub-components. Also, as the class is retired this component's average is not constant over time but decreases significantly.

The SSN 688 class shows constant averages across the sub-components of direct unit cost and a slight decrease in scheduled ship overhaul.

The SSBN 726 class is completely different from the rest. The direct unit cost component is not constant as submarines of the class are coming on line. This could be contributed to the material sub-component of direct unit cost. The direct depot maintenance cost is not constant either. The extreme observations for the 726 class are a result of both the direct unit and direct depot maintenance cost component.



**Figure 6. SSN O&S Sub-Components, DUC and DDC, Averaged by Total Number of Units in a Submarine-Year.** The Average DUC for all three classes are constant from year to year regardless of class retirement or decommissioning. Average DDC is anything but constant from year to year, sharply decreasing for retiring classes 594 and 637 and mildly decreasing for the 688 class which has some decommissioning activity in the later years of the data. The sharp decrease in DDC coincides with the decrease in the extreme observation seen earlier. It's clear that DDC is what drives the extreme observations in submarine O&S cost.



**Figure 7. SSBN O&S Sub-Components, DUC and DDC, Averaged by Total Number of Units in a Submarine-Year.** The Average DUC for the 616 and 640 classes are constant from year to year regardless of class retirement. Average DDC is anything but constant from year to year, sharply decreasing for retiring classes 616 and 640. The sharp decrease in DDC coincides with the decrease in the extreme observation see earlier. The 726 class shows that both DUC and, to a lesser extent, DDC are not constant over time. It's clear that DDC is what drives the extreme observations in the 616 and 640 class O&S cost and primarily DUC for the 726 class.

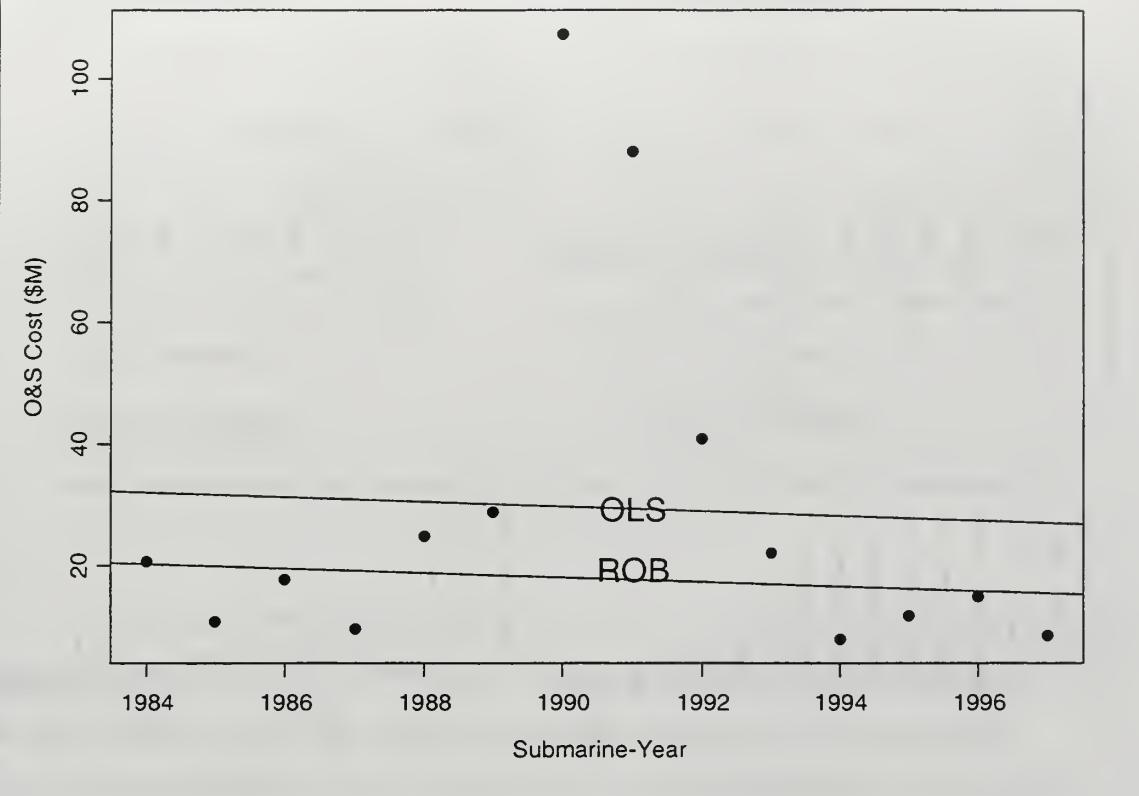
## 5. Regression Analysis

Regression analysis will be used to determine whether average O&S costs are approximately constant from year to year. If the assumption is correct, the analysis should result in a regression line with a zero or near zero slope. However, as shown earlier the data contains many extreme observations which heavily influence OLS. Additionally, we have observed that the histograms are all skewed toward the right, indicating that one of the assumptions of OLS, that the errors are normally distributed might be violated. The influence of extreme observations will tend to overestimate and pull the OLS regression line towards them.

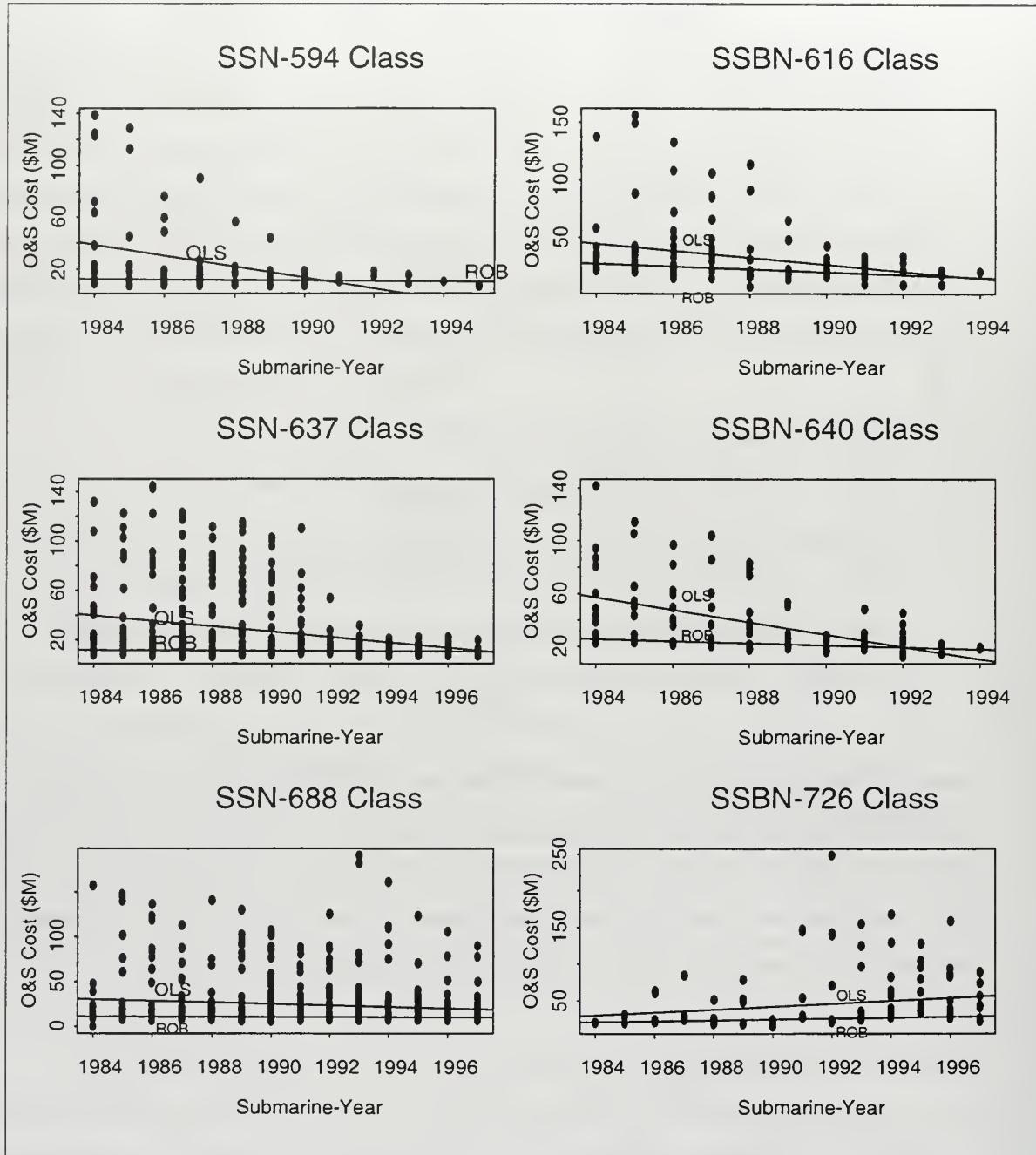
Robust regression (Mathsoft, 1999) techniques are an important complement to the classical ordinary least-squares (OLS) technique in that they provide answers similar to the OLS regression when the data are linear with normally distributed errors, but differ significantly from the OLS fit when the errors don't satisfy the normality condition or when the data contain significant outliers. The Robust regression is influenced by outliers but to a lesser extent than traditional regression. Figure 8 demonstrates this effect by comparing an OLS fit (*S-PLUS* 2000 function *lm( )* (Mathsoft, 1999)) and a Robust fit (*S-PLUS* 2000 function *rreg( )* (Mathsoft, 1999)) with the 671 class data, which has only one submarine. Because the extreme observations are in the middle of the data the OLS fit is pulled toward them like a bar being lifted in the middle to keep its balance. The Robust fit provides a lower estimate of the O&S cost over time and will be used for this analysis. Figure 9 compares OLS and Robust linear regression for the six classes being described.

The Robust fits appear to have a zero or near-zero slope indicating annual O&S costs are constant from year to year. The OLS fit shows indications of a negative slope in all but one case. If the extreme observations were consistently distributed throughout time, the OLS fit would parallel the Robust fit but be shifted up toward the extreme observations. In this case because the direct depot maintenance cost decreases dramatically when a class nears retirement, the OLS fit gets rotated toward the decommissioning years where there are fewer extreme observations.

## OLS and Robust Regression Comparison



**Figure 8. Comparison of OLS and Robust Regression for SSN-671.** Robust regression techniques provide answers similar to the OLS regression when the data are linear with normally distributed errors, but differ significantly from the OLS fit when the errors don't satisfy the normality condition or when the data contains significant outliers. The Robust regression is influenced by outliers but to a lesser extent than traditional regression. This figure demonstrates this effect by comparing an OLS fit and a Robust fit with the 671 class data, which has only one submarine. Because the outliers are in the middle of the data the OLS fit is pulled toward the outliers like a bar being lifted in the middle to keep its balance. The Robust fit provides a lower estimate of the O&S cost over time and will be the used for this analysis.



**Figure 9. OLS and Robust Regression Plots.** Both The OLS and Robust regression lines are displayed but only the robust fit will be analyzed. The Robust fits appear to have a zero or near-zero slope indicating annual O&S costs are approximately constant from year to year. The OLS fit shows indications of a negative slope. If the outliers were consistently distributed through out time, the OLS fit would parallel the Robust fit but shifted up toward the outliers. In this case because the direct depot maintenance cost decreases dramatically when a class nears retirement, the OLS fit gets rotated toward the decommissioning years where there are fewer outliers. This affect is opposite for the 726 class.

Table 2 shows how the Robust regression line fits the data. The predictive measures are the slope of the line, intercept, standard error (SE), coefficient of determination ( $R^2$ ), and t statistic.

Class	Slope of Regression Line (\$M/yr)	Intercept (\$M/yr)	SE	$R^2$	t-stat
594	- .157	324.948	.438	.014	.372
637	- .099	208.386	.061	.006	- 1.619
688	- .083	177.397	.038	.011	- 2.202
616	- 1.19	2391.562	.551	.101	- 2.159
640	- .777	1567.119	.195	.172	- 3.973
726	.615	-1200.779	.199	.158	3.081

**Table 2. Robust regression predictive measures.** All the slopes of the regression lines are very near zero or are insignificant. The  $R^2$ 's at best show no better than .17 which means the regression line explains very little of the variation in the data.

The slope of the regression line indicates how much the average annual O&S cost changes from year to year and although the slope is not zero, it is very close to zero for all but the 616 class. Shortly, the hypothesis that the slopes of the lines in the hypothetical population are zero, will be tested. Since the SE measures the average estimating error when using the model, the smaller the error, the better the fit. Here we see that the errors are on the same order of magnitude as the estimated slope coefficients.  $R^2$  is the percentage of the total variation explained by the regression model. For this indicator, the closer in magnitude that the value is to 1, the better is the fit. All the  $R^2$  values are very low indicating that the regression line doesn't explain the data very well.

The results of table 2 indicate that the regression line does not adequately explain the relationship between total annual O&S cost and ship-year. This means that our assumption that O&S costs are constant over time is plausible. The focus is now shifted to statistical inference and a test of the hypothesis that the slope of the regression line is zero. Table 3 shows the p-values of the t-test for the six submarine classes.

Alpha = 0.05		
Class	Robust Regression (Cost~ Year) p-value	Significant (slope different from zero)
594	.720	No
637	.087	No
688	.028	Yes
616	.032	Yes
640	.000	Yes
726	.003	Yes

**Table 3. t-Test Results.** The results of the t-test indicate that there appears to be a relationship between total annual O&S cost and ship-year for four classes, but this relationship is weak and can in some part be accounted for by the decrease in DDC for retiring classes.

The results of the t-test (Table 3) indicate that there appears to be a relationship between total annual O&S cost and ship-year for four classes. Of these four classes, they all show a decreasing cost over time with the exception of the 726 class, which is increasing over time. There does appear to be a mild indication that total annual O&S cost are not constant over time. However, recalling how the extreme observations affect the data, how a retiring class has a sharp decrease in O&S expenditures, how small the regression slopes are and that the largest  $R^2$  value is less than 18%, it is reasonable to conclude that O&S costs are approximately constant from year to year.

## 6. Data Analysis Conclusion

The original assumption that total annual O&S costs are constant over time is not unreasonable despite evidence of a mild relationship between cost and time. These relationships are characterized in OSD CAIG as the phase in period, steady-state period and the phase-out period. The phase-in period was seen in the SSBN 726 class, the steady-state period was seen in the SSN 688 class and the phase-out period was seen in the other classes. It should be noted that where a trend appears, the cost-time relationship is negative with the exception of the 726 class, meaning O&S cost are decreasing over time for the steady-state period and the phase-out period. Given that the original assumption, which was that O&S cost are constant over time, is not invalid, development of the cost model proceeds with class average data.

## V. FORMULATION OF THE COST MODEL

### A. DEVELOPING THE COST ESTIMATING RELATIONSHIPS

Three parameters related to the size of the submarines, submerged displacement (tons), length overall (LOA) in feet, and manpower (crew), are designated as the independent variables and annual O&S cost as the dependent variable. For each of the thirteen submarine classes submerged displacement, LOA and crew data was collected (Jane's Fighting Ships, 1986-93). The assumption is that as these variables increase, O&S costs will increase. For example, as crew size increases total O&S costs will increase. OLS regression is employed to test this assumption using an  $\alpha$ -level of significance equal to 20 percent<sup>8</sup>. The use of robust regression would be appropriate in this part of the analysis but since the robust results are approximately the same as OLS, OLS is used.

Typically, a point estimate of O&S cost for each class would constitute the O&S cost data for the regression. The point estimate would naturally be the class's average annual O&S cost. The OLS regression would then be conducted on 10 data points or observations comprised of the average O&S cost for each class of submarine in the SSN category and 3 data points or observations comprised of the average O&S cost for each class of submarine in the SSBN category. A point estimate from any of the classes defines the average exactly but says nothing of the variance around the average (recall the scatter plots). By applying a point estimate, information on how O&S costs vary is ignored. As was shown earlier, there is much variability in O&S costs. A better approach is to use all the information that each class provides, the average and the spread around the average. Because it was demonstrated earlier that no submarine is distinguishable from another submarine within its class, it is reasonable to treat each O&S observation within a class as an independent observation.

A multivariate cost model could be problematic as an estimator of total annual O&S cost due to the suspected statistical correlations that exist between the independent variables. To investigate this a correlation matrix was calculated for the independent

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<sup>8</sup> This is the standard level used by analysts in the DOD cost community.

variables (Table 4). The DOD cost-estimating community commonly accepts that correlation values greater than or equal to 70 percent indicate multicollinearity may exist.

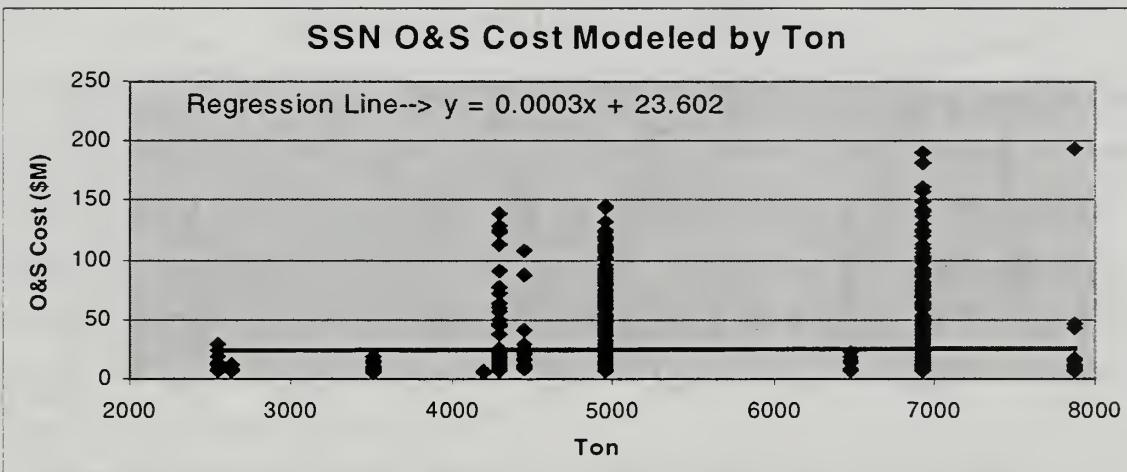
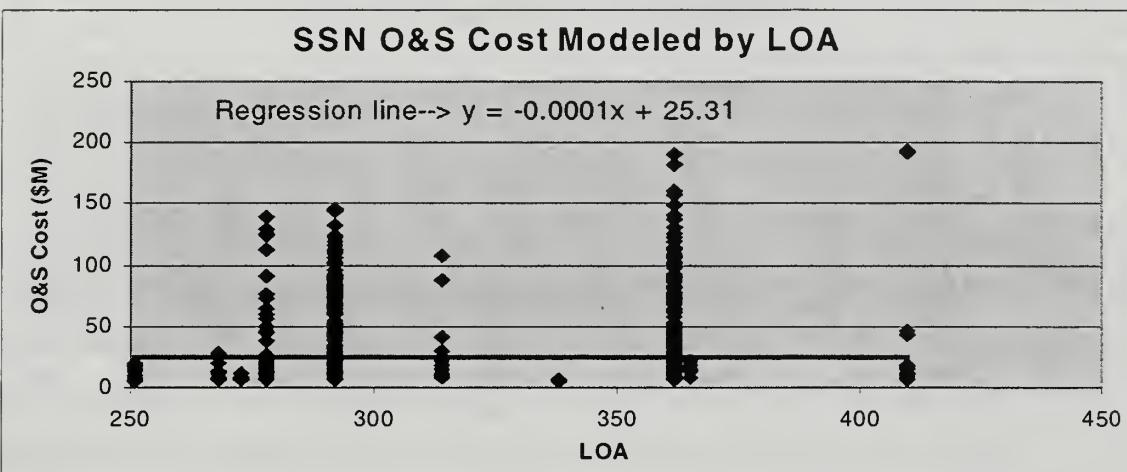
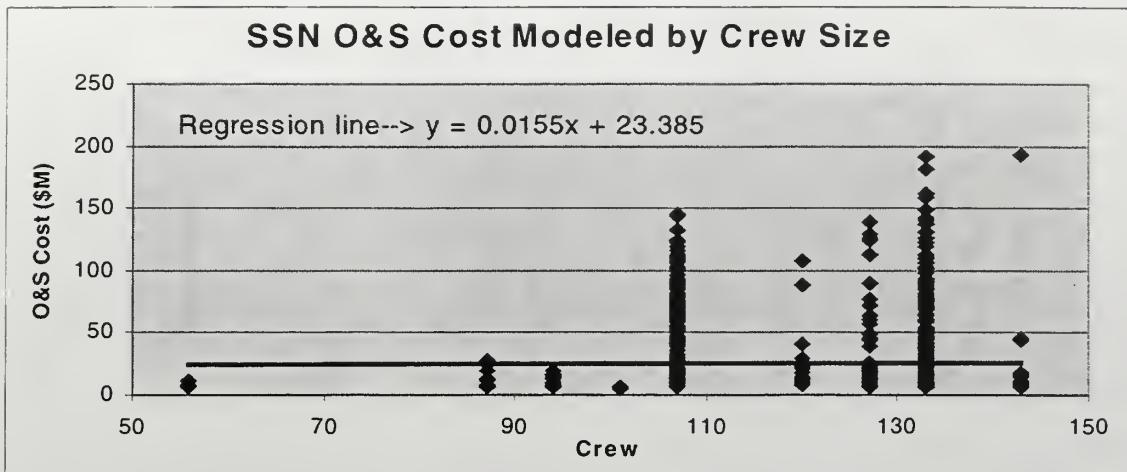
PARAMETERS	Tons	LOA	crew
tons	100%	97.6%	85.4%
LOA	97.6%	100%	85.6%
crew	85.4%	85.6%	100%

**Table 4. Matrix of r-Values for Three Parameters of Submarine Size (SSN).** The correlation matrix for SSBNs is similar.

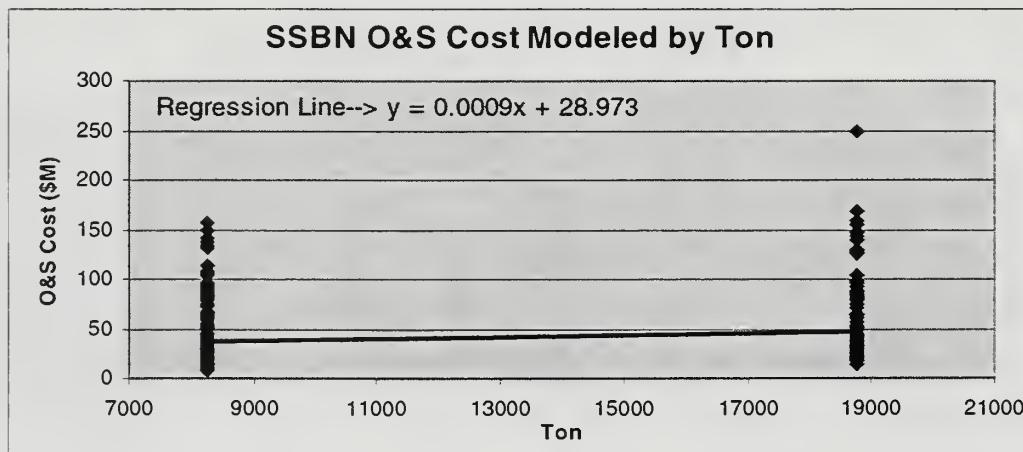
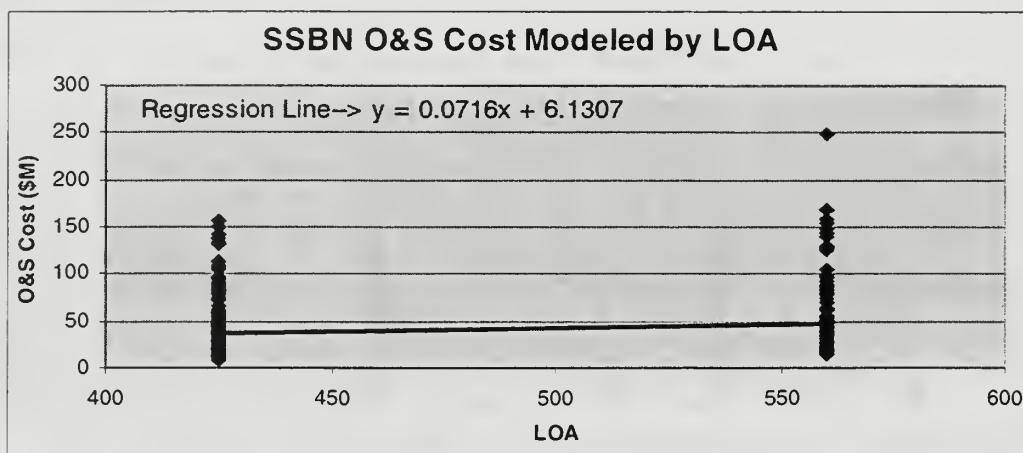
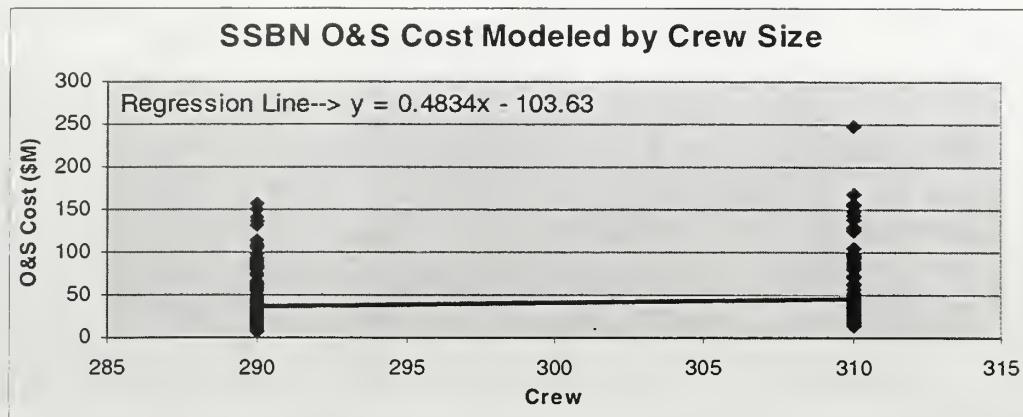
Although all the parameters are statistically dependent, given that their respective *r*-values exceed 80 percent, this study will consider both multivariate and univariate models for completeness. The correlation matrix for SSBNs is similar.

The data analysis chapter highlighted six of the twelve submarine classes used in the study. They were selected to demonstrate the process of visual analysis in validating the assumption that O&S cost are constant across time for any class of submarine. The other six SSN classes made up less than seven percent of the total SSN population and showed similar statistics. This chapter will include all twelve classes in their respective category for the CER analysis.

Graphical analysis of categorical (SSN and SSBN) O&S costs versus size for each class reveals no indication of a close functional relationship for the univariate model (see Figures 10 and 11). The regression lines on the plots indicate that the slopes of all the lines are zero or near zero meaning little change in O&S cost when varying the predictor. The  $R^2$  values show that little to no variation in the data is explained in the model. This indicates that there is no CERs between the three size parameters used and annual O&S costs. Table 5 shows how well the OLS regression lines fit the data. The table introduces a measurement called the coefficient of variation (CV) which is the ratio of the SE to the sample mean. CV is a measure of the percentage by which, on average, the cost prediction will be off from the actual value; thus, a smaller CV implies a better fit.



**Figure 10. SSNs OLS Regression for O&S Cost Modeled by Three Size Parameters.** The regression lines of the three plots reveals no indication of a close CER between O&S cost and submarine size parameter. All  $R^2$  are less than .001, see table 5 for regression results. Additionally, both multiple linear and log-linear modeling was conducted and analyzed but produced similar results (see Appendix B for regression results). This indicates that there is no statistical relationship between the three size parameters and annual O&S costs.



**Figure 11. SSBNs OLS Regression for O&S Cost Modeled by Three Size Parameters.**  
 The regression lines of the three plots reveals no indication of a close CER between O&S cost and submarine size parameter. All  $R^2$  are less than .03, see table 5 for regression results. Additionally, log-linear modeling was conducted and analyzed but produced similar results (see Appendix B for regression results). This indicates that there is no statistical relationship between the three size parameters and annual O&S costs.

Alpha = 0.20							
Category	Slope of Regression Line (\$M)	Intercept (\$M)	SE (\$M)	CV	R <sup>2</sup>	p-Value	Significant (slope different from zero)
SSN – Crew	0.015	23.38	28.85	1.14	.000	0.795	No
SSN – LOA	0.0001	25.31	28.85	1.14	.000	0.995	No
SSN – Tons	0.0003	23.60	28.85	1.14	.000	0.687	No
SSBN - Crew	0.483	-103.63	32.20	.803	.020	0.004	Yes
SSBN – LOA	0.071	6.13	32.20	.803	.020	0.004	Yes
SSBN - Tons	0.0009	28.97	32.20	.803	.020	0.004	Yes

**Table 5. OLS Regression results From O&S Cost Modeled by Three Size Parameters.** The regression lines on the plots indicate that the slopes of all the lines are zero or near-zero meaning little change in O&S cost when varying the predictor. The R<sup>2</sup> values show that little to no variation in the data is explained in the model. This indicates that there is no statistical relationship between the three size parameters and annual O&S costs. The SSN and SSBN CERs explain nothing of O&S costs regardless of the parameter used and the zero slope regression line indicates that O&S costs for all classes in a category, SSN or SSBN, are statistically the same.

The SSN CERs explain virtually nothing of annual O&S costs regardless of the parameter used and the zero slope regression line indicates that annual O&S costs for all SSNs are statistically the same regardless of class. The SSBN CERs also explain very little of O&S costs even though the slope of the regression line is not quite zero. However, it is near zero and does not help model annual O&S cost based on size parameters.

In addition to the above traditional linear regression analysis using a single predictor, both multiple linear regression analysis and log-linear regression analysis was conducted. Multiple linear regression was not conducted on the SSBN category because the three classes in the category have only two different values for each size parameter. SSBN 616 and 640 share the same crew size, LOA and tonnage. The statistics from the analysis indicate that the multiple linear and log-linear models both failed to reveal CERs between the three size parameters used and annual O&S costs. The statistics from the analysis is presented in Appendix B.

The revelation that annual O&S costs are approximately the same for any class within a category may not seem as strange as it appears. For a conventional powered submarine (non-nuke) the amount of diesel fuel used to propel it would be greatly affected by length and displacement. Fuel is a major factor in annual O&S costs for non-

nuclear boats. This fuel must be replenished continuously and thus charged against the boat's O&S cost continuously. For a nuclear powered boat the fuel can be considered as a built-in fuel packet with a set lifetime. The cost of this initial fuel packet is not charged against the boat's annual O&S cost and nuclear fuel is not replenished continuously but discretely. Not all boats are refueled during their lifetime, but the ones that are have an extraordinarily high direct depot maintenance cost component and are observed as some of the extreme observations seen earlier in the data analysis chapter. So we see that the initial cost of fuel is not distributed over the years leading up to a scheduled overhaul with a refueling or decommissioning. Also, when a boat is refueled, it experience a one-time charge against its O&S cost, which will be categorized as an extreme observation. If initial outfitting of reactor cores are charged in the submarines construction phase and reactor cores last the lifetime of the boat, it is possible that the variability in O&S cost may be reduced significantly to where only fleet modernization cost would drive the variance in total O&S cost.

The assumption that annual O&S cost was related to size parameters was the basis of the O&S cost model. With evidence to the contrary, the focus will shift to analysis of the actual cost distribution for SSNs and SSBNs. Examining the cost distributions is an alternate way to estimate annual O&S costs based on probabilistic assessment.

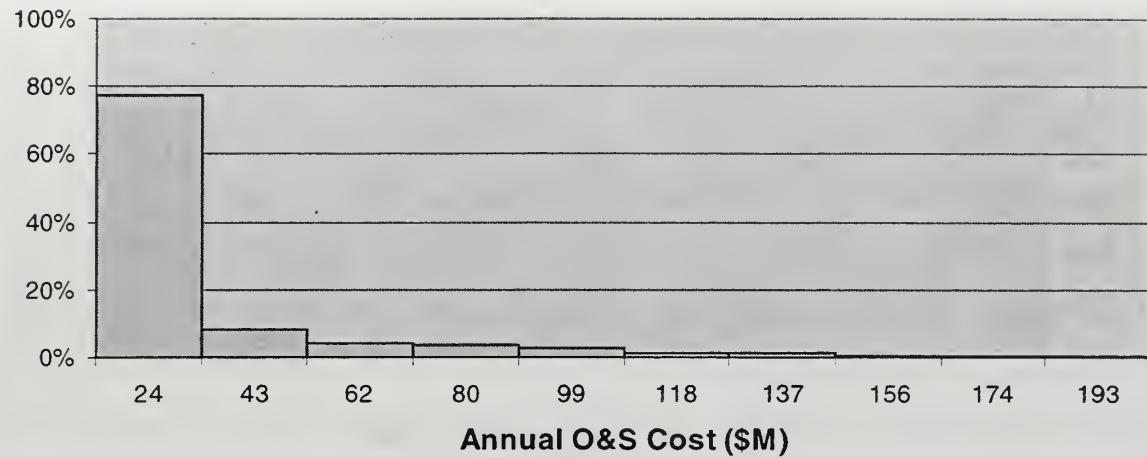
## **B. O&S COST DISTRIBUTION AND CUMULATIVE DISTRIBUTION**

### **1. O&S Cost Distribution and Cumulative Distribution**

Because submarine O&S costs are nearly constant over all classes within the SSN and SSBN categories and can't be modeled with CERs, the distribution of the actual cost data for each category will be analyzed. Through O&S cost distributions and cumulative distributions, decision-makers will have a tool for probabilistic assessment of new submarine acquisition programs.

The distribution of total annual O&S costs for SSN and SSBN categories are displayed in the upper graphs of Figures 12 and 13 and show the relative likelihood of cost falling into different cost ranges. The cost (\$M) under each bar represents the right edge of that bar. The figures show how annual O&S costs are distributed according to

### SSN Annual O&S Cost Distribution



### SSN Annual O&S Cost Cumulative Distribution

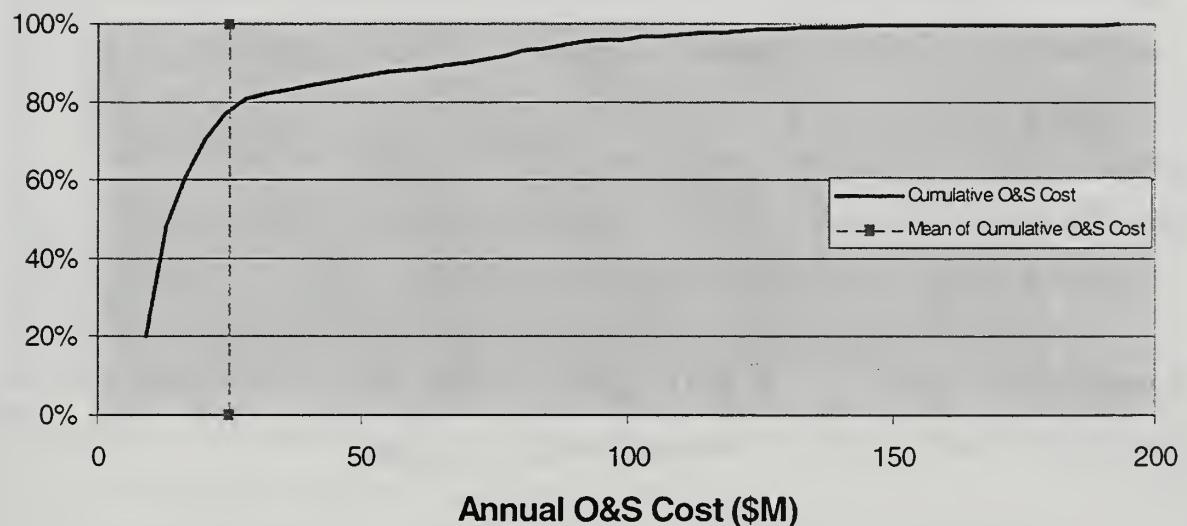
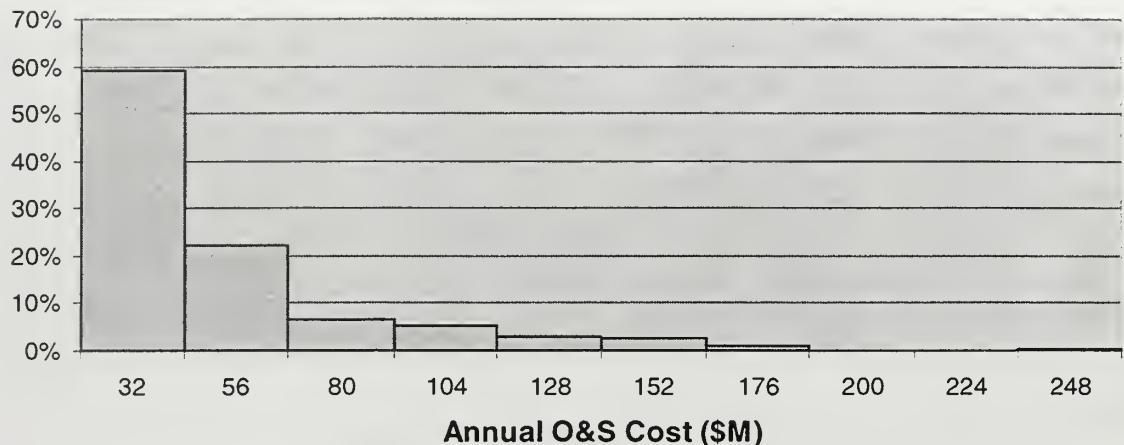
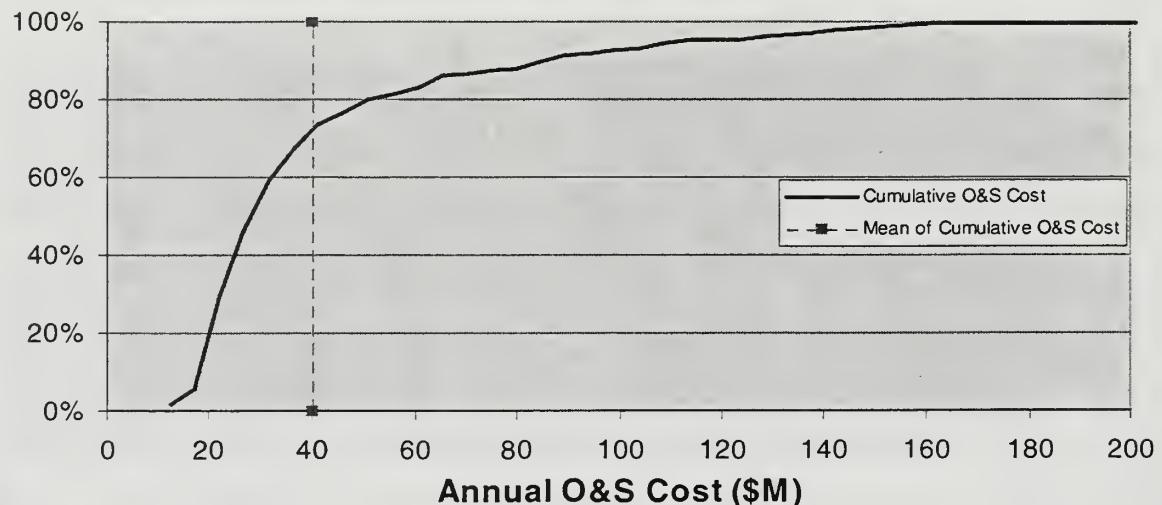


Table 12. SSN Annual O&S Cost Distribution and Cumulative Distribution. An alternate approach to estimating SSN annual O&S Cost is through probabilistic assessment. The O&S cost distribution shows that just under 80% of all O&S cost observations are below \$24 M annually. The cumulative cost distribution shows that 90% of all actual annual O&S cost observations are below \$73 M, and that 10% of all actual observations are above \$73 M. The table at the bottom summarizes the 50<sup>th</sup> through 100<sup>th</sup> percentile of total annual O&S cost.

### SSBN Annual O&S Cost Distribution



### SSBN Annual O&S Cost Cumulative Distribution



50%	60%	70%	80%	90%	100%
\$26 M	\$32 M	\$41 M	\$50 M	\$90 M	\$171 M

**Figure 13. SSBN Annual O&S Cost Distribution and Cumulative Distribution.** An alternate approach to estimating SSBN annual O&S Cost is through probabilistic assessment. The O&S cost distribution shows that 60% of all actual O&S cost observations are below \$32 M annually. The cumulative cost distribution shows that 90% of all actual annual O&S cost observations are below \$90 M, and that 10% of all observations are above \$90 M. The table at the bottom summarizes the 50<sup>th</sup> through 100<sup>th</sup> percentile of total annual O&S cost.

their frequency of occurrence. The frequency of occurrence is expressed as a percentage along the vertical axis and the annual O&S cost along the horizontal axis.

The cumulative distribution of the annual O&S costs provides a probabilistic assessment tool to aid in cost estimation. The cumulative distributions in Figures 12 and 13, along with their associated tables of percentiles, display the cumulative probability that annual O&S cost will be less than or equal to a specified amount for SSNs and SSBNs. The cumulative distribution curves can be read by specifying a probability for which one wants to bound one's cost estimate, and then reading off the corresponding estimate for annual O&S cost. For example, if a decision maker or cost analyst desires an SSN annual O&S cost estimate for which the probability is 80 percent that the true annual O&S cost will not exceed the estimate, then, looking at Figure 12, the analyst would find 80 percent on the vertical axis and read off approximately \$27 M on the horizontal axis. The interpretation is that, historically, 80 percent of all SSNs have experienced annual O&S costs of no more than \$27 M, while 20 percent of SSNs experienced higher annual costs. Or, loosely, the analyst can be about 80 percent confident that annual O&S costs for the new submarine will not exceed \$27 M. Similarly, suppose one wants a cost estimate for which the probability is 90 percent that the true annual O&S cost will not exceed the estimate. This time the analyst would find 90 percent on the vertical axis and read off approximately \$73 M on the horizontal axis. Again, the interpretation is that, historically, 90 percent of all SSNs experienced annual O&S costs less than or equal to \$73 M, while 10 percent of all SSNs had annual O&S cost greater than \$73 M. The percentile table in Figure 12 and 13 simplify this lookup for selected cumulative probabilities.

It is worthwhile pointing out that points along those segments of the cumulative distribution curve which tend to the vertical have relatively small variance, while points along the those segments which tend to the horizontal have significantly larger variance.

In addition, the cumulative distribution of the four major O&S cost components for both SSNs and SSBNs are also broken out and listed in Appendices E and F. These are given in the event that one desires to estimate submarine annual O&S costs at the O&S sub-component level.

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## VI. CONCLUSIONS AND RECOMMENDATION

The assumption that submarine annual O&S costs could be estimated using simple predictors such as crew size, length overall and submerged displacement was shown to be invalid. The results of the analysis showed that the annual O&S costs are roughly the same across all classes within a category, SSN or SSBN. However, the analysis also showed that extreme annual O&S cost observations are common and that these extreme observations tend to be driven by depot maintenance costs.

With the failure of the parametric models, an alternative method of estimating annual O&S cost was developed using probabilistic assessment of cost based on the empirical annual O&S cost distribution. Although the process lacks precision, it provides bounded cost estimates based on 14 years worth of real O&S cost data. The probabilistic assessment method allows decision makers and cost analysts to estimate the annual O&S cost for which there is a desired probability that the true annual O&S cost of a new submarine will not be exceeded. For example, analysts can determine that, historically, 80 percent of all SSNs have experienced annual O&S costs of less than \$27 M (CY99\$), while the remaining 20 percent have experienced annual O&S costs greater than \$27 M (CY99\$). So, loosely speaking, one can be approximately 80 percent confident that the annual O&S cost of a newly acquired SSN will be no more than \$27 M (CY99\$). Similar results can be obtained for any SSN or SSBN, and for any desired probability.

Further investigation is recommended to gain insight into the specific causes of the extreme annual O&S cost observations. A better understanding of their causes could affect acquisition strategy and possibly reduce the variance in annual O&S costs, which would ultimately improve the ability to estimate annual O&S cost of new submarines.

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## APPENDIX A. SAMPLE OF RAW VAMOSC-ISR DATA

SSN-  
671CL

			1984
	BARRELS (BBLS) FUEL PER STEAMING HOUR UNDERWAY	SSN-671 NARWHAL	0
	NO. OF ENLISTED PERSONNEL - MARINE	SSN-671 NARWHAL	0
	NO. OF ENLISTED PERSONNEL - NAVY	SSN-671 NARWHAL	125
	NO. OF OFFICER PERSONNEL - MARINE	SSN-671 NARWHAL	0
	NO. OF OFFICER PERSONNEL - NAVY	SSN-671 NARWHAL	15
	NO. OF SHIPS	SSN-671 NARWHAL	1
	STEAMING HOURS NOT UNDERWAY	SSN-671 NARWHAL	192
	STEAMING HOURS UNDERWAY	SSN-671 NARWHAL	2,860.00
<b>1.0</b>	<b>DIRECT UNIT COSTS</b>	SSN-671 NARWHAL	7,233,143.00
1.1	PERSONNEL	SSN-671 NARWHAL	4,690,610.00
1.1.1	MANPOWER	SSN-671 NARWHAL	4,666,473.00
1.1.1.1	REPORTED MAINTENANCE LABOR MANHOURS	SSN-671 NARWHAL	4,807.00
1.1.1.2	OFFICER MANPOWER	SSN-671 NARWHAL	874,502.00
1.1.1.3	ENLISTED MANPOWER	SSN-671 NARWHAL	3,791,971.00
1.1.2	TEMPORARY ADDITIONAL DUTY (TAD)	SSN-671 NARWHAL	24,138.00
1.2	MATERIAL	SSN-671 NARWHAL	2,288,133.00
1.2.1	SHIP PETROLEUM, OIL AND LUBRICANTS (POL)	SSN-671 NARWHAL	27,809.00
1.2.1.1	FUEL (FOSSIL)	SSN-671 NARWHAL	15,244.00
1.2.1.1.1	FUEL UNDERWAY	SSN-671 NARWHAL	12,042.00
1.2.1.1.2	FUEL NOT UNDERWAY	SSN-671 NARWHAL	3,202.00
1.2.1.2	OTHER PETROLEUM, OIL AND LUBRICANTS (POL)	SSN-671 NARWHAL	12,564.00
1.2.1.3	BARRELS OF FUEL CONSUMED	SSN-671 NARWHAL	24
1.2.1.3.1	UNDERWAY	SSN-671 NARWHAL	19
1.2.1.3.2	NOT UNDERWAY	SSN-671 NARWHAL	5
1.2.2	REPAIR PARTS	SSN-671 NARWHAL	652,563.00
1.2.3	SUPPLIES	SSN-671 NARWHAL	270,882.00
1.2.3.1	EQUIPMENT/EQUIPAGE	SSN-671 NARWHAL	37,434.00
1.2.3.2	CONSUMABLES	SSN-671 NARWHAL	182,676.00
1.2.3.3	SHIPS FORCE MATERIAL	SSN-671 NARWHAL	50,772.00
1.2.4	TRAINING EXPENDABLE STORES	SSN-671 NARWHAL	4,863.00
1.2.4.1	AMMUNITION	SSN-671 NARWHAL	4,863.00
1.2.4.2	OTHER EXPENDABLES	SSN-671 NARWHAL	0
1.2.5	REPAIRABLES	SSN-671 NARWHAL	1,332,016.00
1.2.5.1	ORGANIZATIONAL EXCHANGES	SSN-671 NARWHAL	1,084,977.00
1.2.5.2	ORGANIZATIONAL ISSUES	SSN-671 NARWHAL	247,038.00
1.3	PURCHASED SERVICES	SSN-671 NARWHAL	254,399.00
1.3.1	PRINTING AND REPRODUCTION	SSN-671 NARWHAL	0
1.3.2	ADP RENTAL AND CONTRACT SERVICES	SSN-671 NARWHAL	0
1.3.3	RENT AND UTILITIES	SSN-671 NARWHAL	232,228.00
1.3.4	COMMUNICATIONS	SSN-671 NARWHAL	0
1.3.5	OTHER	SSN-671 NARWHAL	22,171.00
<b>2.0</b>	<b>DIRECT INTERMEDIATE MAINTENANCE</b>	SSN-671 NARWHAL	455,523.00
2.1	AFLOAT MAINTENANCE LABOR	SSN-671 NARWHAL	345,835.00
2.1.1	AFLOAT MAINTENANCE LABOR	SSN-671 NARWHAL	19,392.00

MANHOURS				
2.2	ASHORE MAINTENANCE LABOR	SSN-671	NARWHAL	11,985.00
2.2.1	ASHORE MAINTENANCE LABOR	SSN-671	NARWHAL	672
	MANHOURS			
2.3	MATERIAL (DIM)	SSN-671	NARWHAL	97,703.00
2.3.1	AFLOAT REPAIR PARTS	SSN-671	NARWHAL	71,833.00
2.3.2	ASHORE REPAIR PARTS	SSN-671	NARWHAL	5,182.00
2.4	COMMERCIAL INDUSTRIAL SERVICES	SSN-671	NARWHAL	
<b>3.0</b>	<b>DIRECT DEPOT MAINTENANCE</b>	<b>SSN-671</b>	<b>NARWHAL</b>	<b>12,542,121.00</b>
3.1	SCHEDULED SHIP OVERHAUL	SSN-671	NARWHAL	7,315,412.00
3.1.1	REGULAR OVERHAUL	SSN-671	NARWHAL	11,409.00
3.1.1.1	PUBLIC SHIPYARD (ROH)	SSN-671	NARWHAL	0
3.1.1.1.1	OVERHEAD (ROH PUBLIC)	SSN-671	NARWHAL	0
3.1.1.1.2	LABOR (ROH PUBLIC)	SSN-671	NARWHAL	0
3.1.1.1.2.1	MANDAYS (ROH PUBLIC)	SSN-671	NARWHAL	0
3.1.1.1.3	MATERIAL (ROH PUBLIC)	SSN-671	NARWHAL	0
3.1.1.2	PRIVATE SHIPYARD (ROH)	SSN-671	NARWHAL	REMOVED
3.1.1.3	SHIP REPAIR FACILITY (ROH)	SSN-671	NARWHAL	0
3.1.1.3.1	OVERHEAD (ROH SRF)	SSN-671	NARWHAL	0
3.1.1.3.2	LABOR (ROH SRF)	SSN-671	NARWHAL	0
3.1.1.3.3	MATERIAL (ROH SRF)	SSN-671	NARWHAL	0
3.1.2	SELECTED RESTRICTED AVAILABILITY (SRA)	SSN-671	NARWHAL	7,304,003.00
3.1.2.1	PUBLIC SHIPYARD (SRA)	SSN-671	NARWHAL	7,304,003.00
3.1.2.1.1	OVERHEAD (SRA PUBLIC)	SSN-671	NARWHAL	REMOVED
3.1.2.1.2	LABOR (SRA PUBLIC)	SSN-671	NARWHAL	REMOVED
3.1.2.1.2.1	MANDAYS (SRA PUBLIC)	SSN-671	NARWHAL	REMOVED
3.1.2.1.3	MATERIAL (SRA PUBLIC)	SSN-671	NARWHAL	1,148,041.00
3.1.2.2	PRIVATE SHIPYARD (SRA)	SSN-671	NARWHAL	0
3.1.2.3	SHIP REPAIR FACILITY (SRA)	SSN-671	NARWHAL	0
3.1.2.3.1	OVERHEAD (SRA SRF)	SSN-671	NARWHAL	0
3.1.2.3.2	LABOR (SRA SRF)	SSN-671	NARWHAL	0
3.1.2.3.3	MATERIAL (SRA SRF)	SSN-671	NARWHAL	0
3.2	NONSCHEDULED SHIP REPAIRS	SSN-671	NARWHAL	22,894.00
3.2.1	RESTRICTED AVAILABILITY	SSN-671	NARWHAL	0
3.2.1.1	PUBLIC SHIPYARD (RAV)	SSN-671	NARWHAL	0
3.2.1.1.1	OVERHEAD (RAV PUBLIC)	SSN-671	NARWHAL	0
3.2.1.1.2	LABOR (RAV PUBLIC)	SSN-671	NARWHAL	0
3.2.1.1.2.1	MANDAYS (RAV PUBLIC)	SSN-671	NARWHAL	0
3.2.1.1.3	MATERIAL (RAV PUBLIC)	SSN-671	NARWHAL	0
3.2.1.2	PRIVATE SHIPYARD (RAV)	SSN-671	NARWHAL	0
3.2.1.3	SHIP REPAIR FACILITY (RAV)	SSN-671	NARWHAL	0
3.2.1.3.1	OVERHEAD (RAV SRF)	SSN-671	NARWHAL	0
3.2.1.3.2	LABOR (RAV SRF)	SSN-671	NARWHAL	0
3.2.1.3.3	MATERIAL (RAV SRF)	SSN-671	NARWHAL	0
3.2.2	TECHNICAL AVAILABILITY (TAV)	SSN-671	NARWHAL	22,894.00
3.2.2.1	PUBLIC SHIPYARD (TAV)	SSN-671	NARWHAL	22,894.00
3.2.2.1.1	OVERHEAD (TAV PUBLIC)	SSN-671	NARWHAL	REMOVED
3.2.2.1.2	LABOR (TAV PUBLIC)	SSN-671	NARWHAL	REMOVED
3.2.2.1.2.1	MANDAYS (TAV PUBLIC)	SSN-671	NARWHAL	REMOVED
3.2.2.1.3	MATERIAL (TAV PUBLIC)	SSN-671	NARWHAL	REMOVED
3.2.2.2	PRIVATE SHIPYARD (TAV)	SSN-671	NARWHAL	0

3.2.2.3	SHIP REPAIR FACILITY (TAV)	SSN-671 NARWHAL	0
3.2.2.3.1	OVERHEAD (TAV SRF)	SSN-671 NARWHAL	0
3.2.2.3.2	LABOR (TAV SRF)	SSN-671 NARWHAL	0
3.2.2.3.3	MATERIAL (TAV SRF)	SSN-671 NARWHAL	0
3.3	FLEET MODERNIZATION	SSN-671 NARWHAL	4,964,238.00
3.3.1	PUBLIC SHIPYARD (FM)	SSN-671 NARWHAL	1,464,702.00
3.3.1.1	OVERHEAD (FM PUBLIC)	SSN-671 NARWHAL	REMOVED
3.3.1.2	LABOR (FM PUBLIC)	SSN-671 NARWHAL	REMOVED
3.3.1.2.1	MANDAYS (FM PUBLIC)	SSN-671 NARWHAL	REMOVED
3.3.1.3	MATERIAL (FM PUBLIC)	SSN-671 NARWHAL	87,574.00
3.3.2	PRIVATE SHIPYARD (FM)	SSN-671 NARWHAL	
3.3.3	SHIP REPAIR FACILITY (FM)	SSN-671 NARWHAL	0
3.3.3.1	OVERHEAD (FM SRF)	SSN-671 NARWHAL	0
3.3.3.2	LABOR (FM SRF)	SSN-671 NARWHAL	0
3.3.3.3	MATERIAL (FM SRF)	SSN-671 NARWHAL	0
3.3.4	CENTRALLY-PROVIDED MATERIAL	SSN-671 NARWHAL	2,886,656.00
3.3.5	OTHER (FM)	SSN-671 NARWHAL	514,898.00
3.3.6	OUTFITTING AND SPARES	SSN-671 NARWHAL	
3.4	OTHER DEPOT	SSN-671 NARWHAL	337,558.00
3.4.1	NAVAL AVIATION DEPOT (NADEP)	SSN-671 NARWHAL	0
3.4.1.1	OVERHEAD (NADEP)	SSN-671 NARWHAL	0
3.4.1.2	LABOR (NADEP)	SSN-671 NARWHAL	0
3.4.1.3	MATERIAL (NADEP)	SSN-671 NARWHAL	0
3.4.2	FIELD CHANGE INSTALLATION	SSN-671 NARWHAL	0
3.4.3	REWORK	SSN-671 NARWHAL	248,018.00
3.4.3.1	ORDNANCE REWORK	SSN-671 NARWHAL	0
3.4.3.2	HULL, MECHANICAL AND ELECTRICAL REWORK (HME)	SSN-671 NARWHAL	248,018.00
3.4.3.3	ELECTRONIC REWORK	SSN-671 NARWHAL	0
3.4.4	DESIGN SERVICES ALLOCATION	SSN-671 NARWHAL	89,541.00
3.4.5	PERA, SUBMEPP PLANNING AND PROCUREMENT	SSN-671 NARWHAL	
3.4.5.1	PERA, SUBMEPP PLANNING	SSN-671 NARWHAL	
3.4.5.2	PERA, SUBMEPP PROCUREMENT	SSN-671 NARWHAL	
<b>4.0</b>	<b>INDIRECT OPERATING AND SUPPORT</b>	SSN-671 NARWHAL	615,255.00
4.1	TRAINING	SSN-671 NARWHAL	537,383.00
4.2	PUBLICATIONS	SSN-671 NARWHAL	2,651.00
4.3	ENGINEERING AND TECHNICAL SERVICE (ETS)	SSN-671 NARWHAL	75,222.00
4.4	AMMUNITION HANDLING	SSN-671 NARWHAL	0
<b>5.0</b>	<b>TOTAL</b>	SSN-671 NARWHAL	20,616,881.00

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## APPENDIX B. MULTIPLE LINEAR AND LOG-LINEAR REGRESSION ANALYSIS

Multiple Linear Regression Results (None for SSBN category)

### 1. SSN

a. O&S cost ~ Crew + LOA + Ton

Predictors	Slope (\$M)	SE (\$M)	t-stat	p-value
Crew	.024	.117	.204	.838
LOA	-.184	.100	-1.835	.066
Ton	.006	.003	1.815	.069
Intercept (\$M)	47.644	14.991	3.178	.001

$R^2$	0.00295
f-statistic / p-value	1.186 / .313
Significant Alpha = .20	No

b. O&S cost ~ Crew + LOA

Predictors	Slope (\$M)	SE (\$M)	t-stat	p-value
Crew	.059	.116	.510	.610
LOA	-.018	.041	-.439	.660
Intercept (\$M)	24.05	7.486	3.212	.001

$R^2$	.0002
f-statistic / p-value	.130 / .878
Significant Alpha = .20	No

c. O&S cost ~ Crew + Ton

Predictors	Slope (\$M)	SE (\$M)	t-stat	p-value
Crew	-.018	.115	-.162	.870
Ton	.000	.001	.348	.727
Intercept (\$M)	24.770	8.343	2.969	.003

$R^2$	.0001
f-statistic / p-value	.094 / .910
Significant Alpha = .20	No

d. O&S cost ~ Ton + LOA

Predictors	Slope (\$M)	SE (\$M)	t-stat	p-value
Ton	.006	.003	1.875	.060
LOA	-.180	.098	-1.832	.067
Intercept (\$M)	48.578	14.271	3.403	.000

$R^2$	.0029
f-statistic / p-value	1.76 / .1726
Significant Alpha = .20	Yes

## Log-Linear Regression Results

1. SSN

a.  $\ln(\text{O&S cost}) \sim \ln(\text{Crew}) + \ln(\text{LOA}) + \ln(\text{Ton})$

Predictors	Slope	SE	t-stat	p-value
$\ln(\text{Crew})$	.1560	.3359	.464	.642
$\ln(\text{LOA})$	-2.0712	.6113	-3.388	.000
$\ln(\text{Ton})$	1.0585	.3456	3.352	.000
Intercept	4.0561	1.1491	3.529	.000

$R^2$	.011
f-statistic / p-value	4.476 / .004
Significant Alpha = .20	Yes

b.  $\ln(\text{O\&S cost}) \sim \ln(\text{Crew}) + \ln(\text{LOA})$

Predictors	Slope	SE	t-stat	p-value
$\ln(\text{Crew})$	.468	.324	1.446	.148
$\ln(\text{LOA})$	-.340	.328	-1.036	.300
Intercept	2.578	1.065	2.419	.015

$R^2$	.0018
f-statistic / p-value	1.087 / .3376
Significant $\text{Alpha} = .20$	No

c.  $\ln(\text{O\&S cost}) \sim \ln(\text{Crew}) + \ln(\text{Ton})$

Predictors	Slope	SE	t-stat	p-value
$\ln(\text{Crew})$	-.062	.331	-.187	.851
$\ln(\text{Ton})$	.169	.185	.912	.361
Intercept	1.684	.915	1.840	.066

$R^2$	.0016
f-statistic / p-value	.965 / .381
Significant $\text{Alpha} = .20$	No

d.  $\ln(\text{O\&S cost}) \sim \ln(\text{Ton}) + \ln(\text{LOA})$

Predictors	Slope	SE	t-stat	p-value
$\ln(\text{Ton})$	1.203	.331	3.624	.000
$\ln(\text{LOA})$	-2.016	.599	-3.362	.000
Intercept	4.103	1.144	3.586	.000

$R^2$	.0109
f-statistic / p-value	6.611 / .001
Significant $\text{Alpha} = .20$	Yes

e.  $\ln(\text{O\&S cost}) \sim \ln(\text{Crew})$

Predictors	Slope	SE	t-stat	p-value
$\ln(\text{Crew})$	.190	.181	1.048	.294
Intercept	1.941	.870	2.230	.025

CV	.063
$R^2$	.0009
p-value	.294
Significant $\text{Alpha} = .20$	No

f.  $\ln(\text{O\&S cost}) \sim \ln(\text{LOA})$

Predictors	Slope	SE	t-stat	p-value
$\ln(\text{LOA})$	.052	.184	.287	.774
Intercept	2.548	1.066	2.390	.017

CV	.064
$R^2$	.000
p-value	.774
Significant $\text{Alpha} = .20$	No

g.  $\ln(\text{O\&S cost}) \sim \ln(\text{Ton})$

Predictors	Slope	SE	t-stat	p-value
$\ln(\text{Ton})$	.140	.102	1.377	.168
Intercept	1.639	.882	1.857	.063

CV	.035
$R^2$	.001
p-value	.168
Significant $\text{Alpha} = .20$	Yes

## 2. SSBN

a.  $\ln(\text{O\&S cost}) \sim \ln(\text{Crew})$

Predictors	Slope	SE	t-stat	p-value
$\ln(\text{Crew})$	2.917	.938	3.107	.002
Intercept	-13.13	5.345	-2.457	.014

CV	.270
$R^2$	.024
p-value	.002
Significant <i>Alpha</i> = .20	Yes

b.  $\ln(\text{O\&S cost}) \sim \ln(\text{LOA})$

Predictors	Slope	SE	t-stat	p-value
$\ln(\text{LOA})$	.705	.227	3.107	.002
Intercept	-.863	1.396	-0.618	.536

CV	.065
$R^2$	.024
p-value	.002
Significant <i>Alpha</i> = .20	Yes

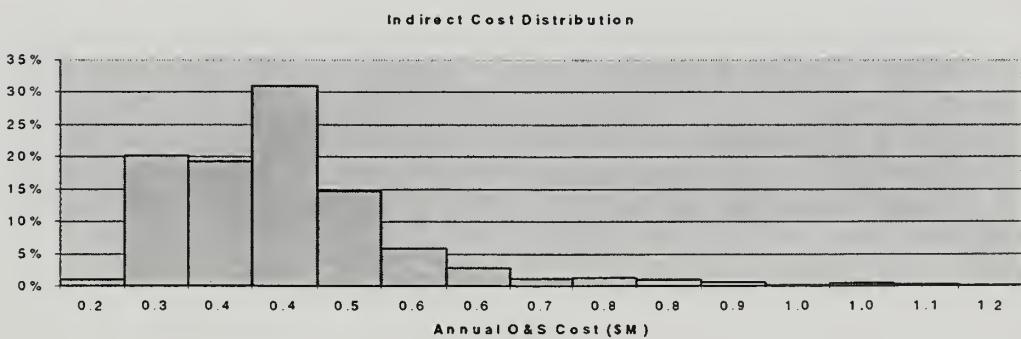
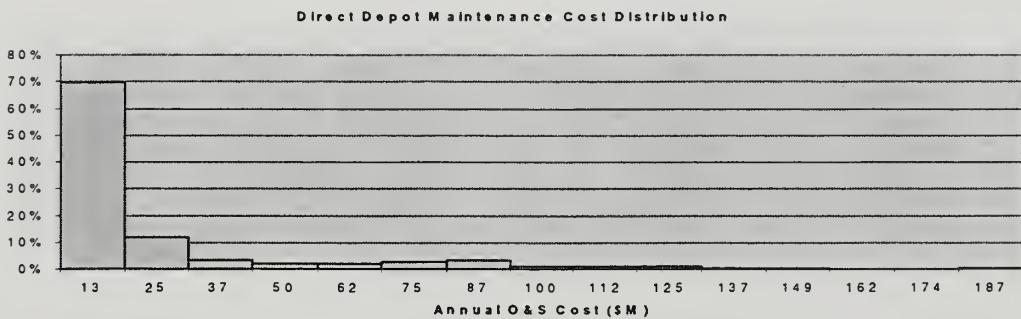
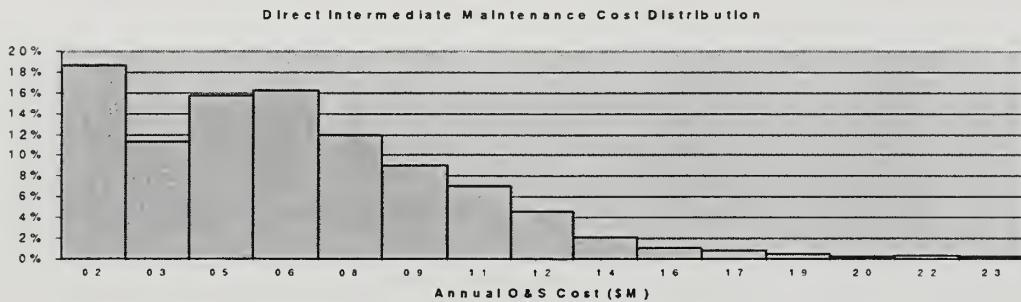
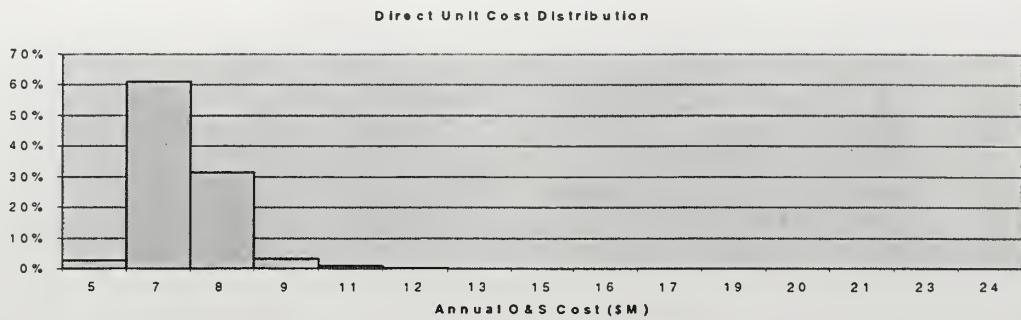
c.  $\ln(\text{O\&S cost}) \sim \ln(\text{Ton})$

Predictors	Slope	SE	t-stat	p-value
$\ln(\text{Ton})$	.237	.076	3.107	.002
Intercept	1.268	.711	1.783	.075

CV	.022
$R^2$	.024
p-value	.002
Significant <i>Alpha</i> = .20	Yes

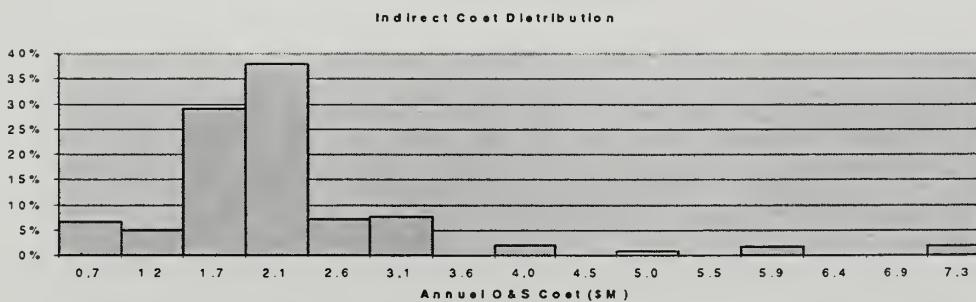
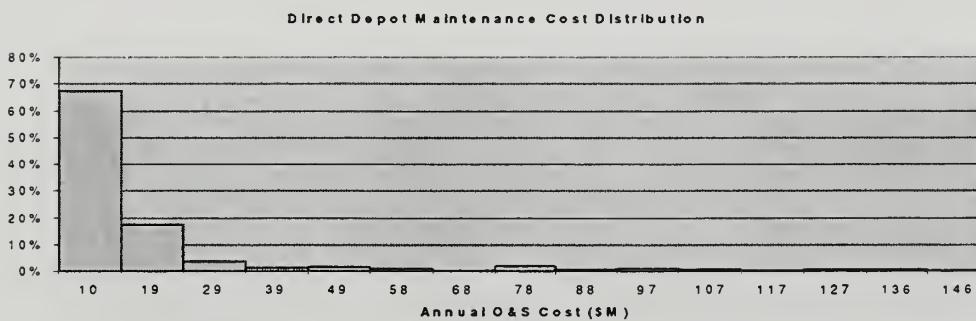
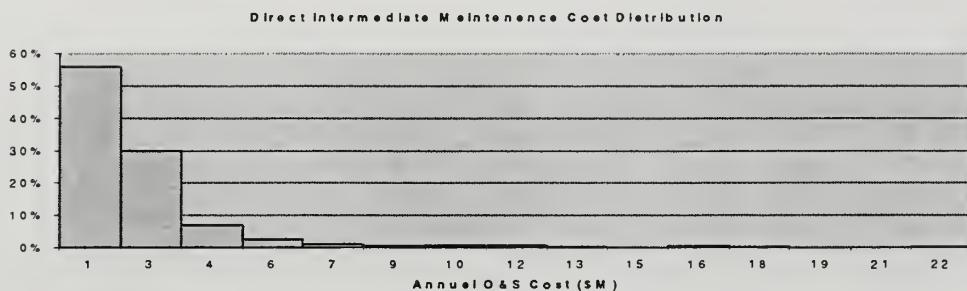
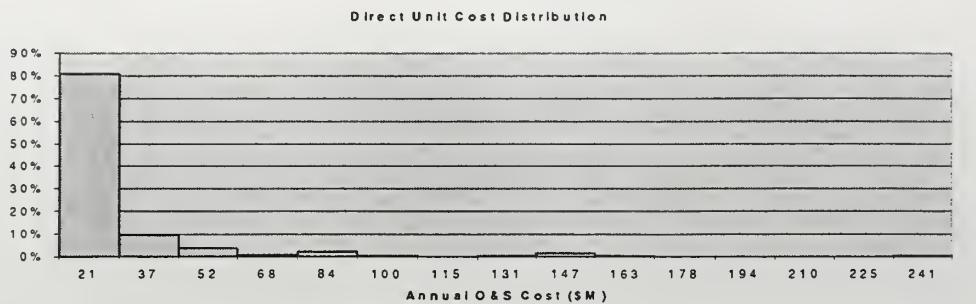
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## APPENDIX C. SSN COMPONENT ANNUAL O&S COST DISTRIBUTIONS



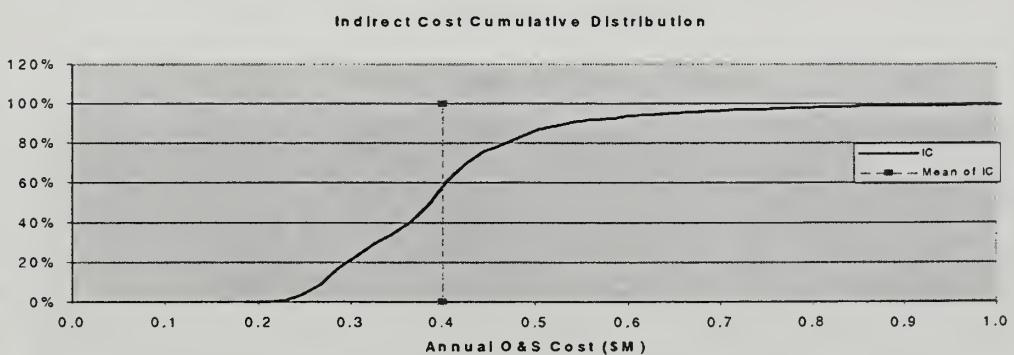
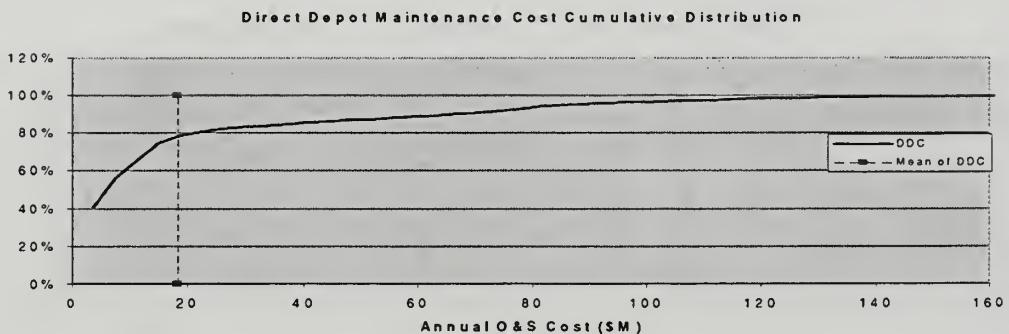
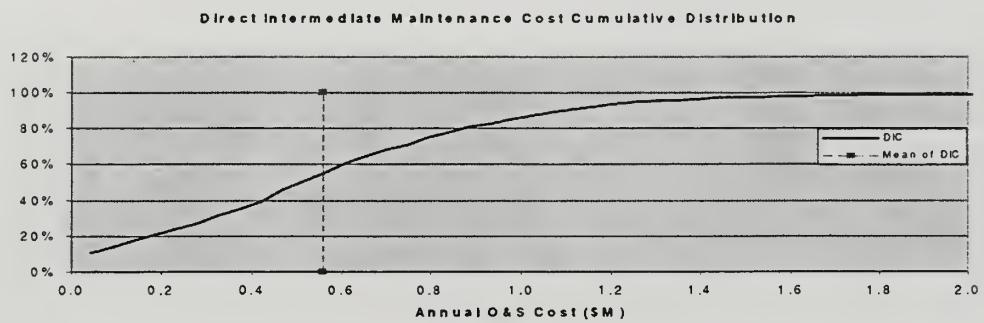
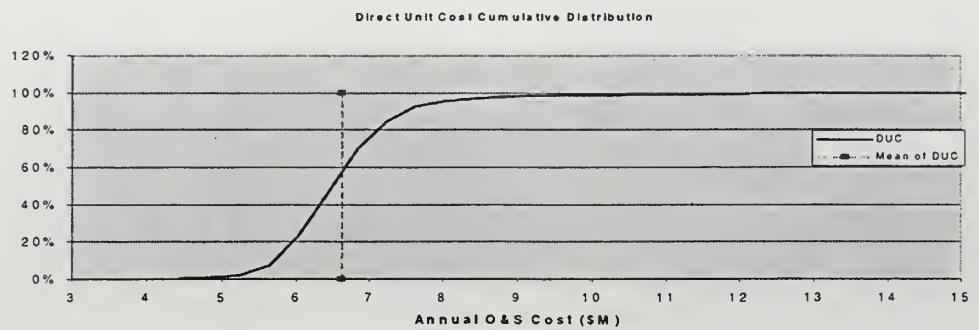
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## APPENDIX D. SSBN COMPONENT ANNUAL O&S COST DISTRIBUTIONS



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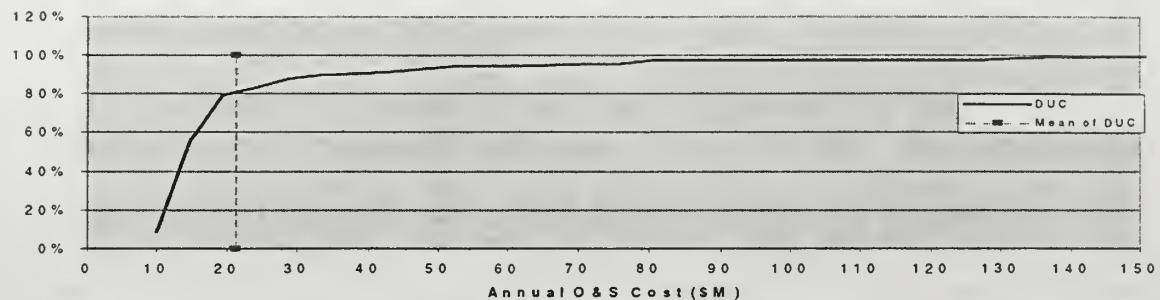
## APPENDIX E. SSN COMPONENT ANNUAL O&S COST CUMULATIVE DISTRIBUTIONS



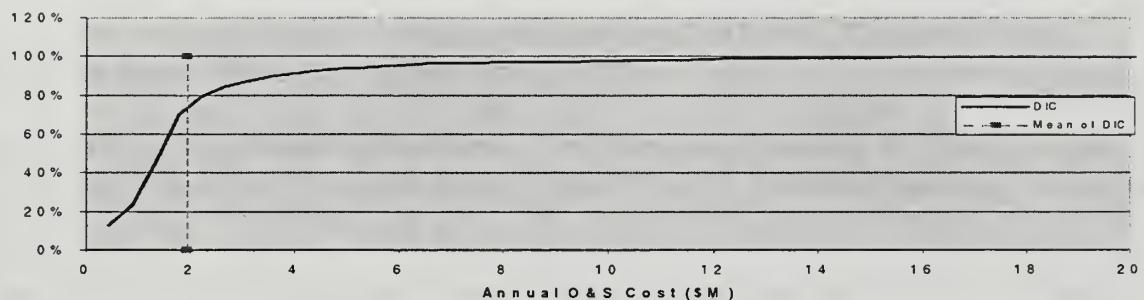
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## APPENDIX F. SSBN COMPONENT ANNUAL O&S COST CUMULATIVE DISTRIBUTIONS

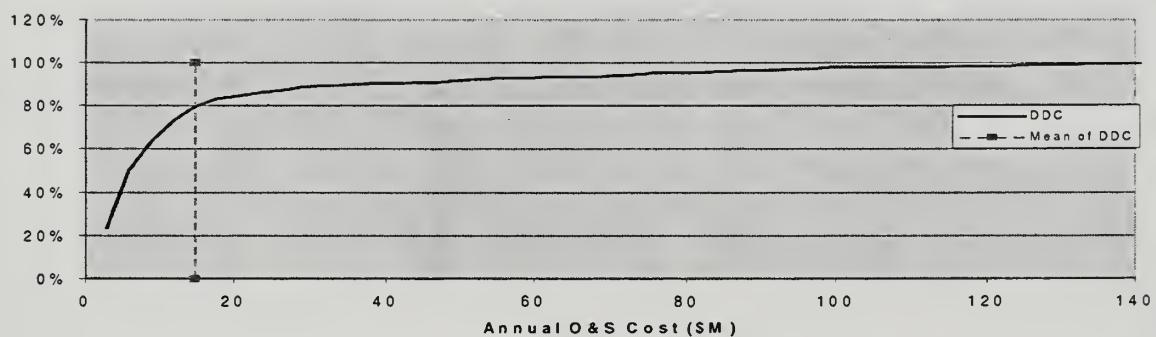
Direct Unit Cost Cumulative Distribution



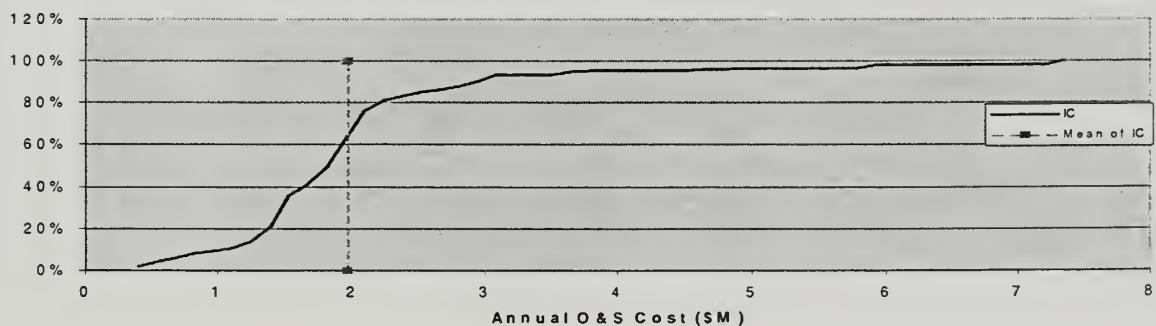
Direct Intermediate Maintenance Cost Cumulative Distribution



Direct Depot Maintenance Cost Cumulative Distribution



Indirect Cost Cumulative Distribution



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